Bachelor's thesis

Automotive Engineering

2015

Georgios Rolis

EXPERIMENTAL STUDY OF AN OFF-ROAD ENGINE WITH RESPECT TO GASEOUS AND PARTICULATE EMISSIONS OVER DIFFERENT EXHAUST AFTERTREATMENT CONFIGURATIONS

TURUN AMMATTIKORKEAKOULU
TURKU UNIVERSITY OF APPLIED SCIENCES

BACHELOR´S THESIS | ABSTRACT
TURKU UNIVERSITY OF APPLIED SCIENCES

Degree in Engineering | Automotive Engineering

December 2015| Total number of pages: 89

Mika Lauren

Georgios Rolis

EXPERIMENTAL STUDY OF AN OFF-ROAD ENGINE WITH RESPECT TO GASEOUS AND PARTICULATE EMISSIONS OVER DIFFERENT EXHAUST AFTERTREATMENT CONFIGURATIONS

This bachelor's thesis introduces one of the measurement campaigns of HERE project that took place during spring of 2015. Particularly, this thesis aims to examine the many particulate measurement analyzers used by TUAS and other research partners. Moreover, the purpose of this thesis is to research particulate emissions of a combustion engine and to study new methods in order to analyze particulate emissions. A main outcome of the effort is to provide findings that have the potential to affect emission legislation.

In essence, this thesis consists of two parts: theory and measurement data analysis. In the first part, a review of particulate measurement legislation in combustion engines at present is provided as well as a short introduction of common particulate analysis systems. In the experimental part, engine performance and gaseous emission data of dynamometer tests are analyzed and graphs are constructed to present these results.

KEYWORDS:

Diesel, engine, SCR, fSCR, DOC, DPF, EGR, Adblue, aftertreatment, UREA, HERE, NRSC

ΠΤΥΧΙΑΚΗ ΕΡΓΑΣΙΑ | ΠΕΡΙΛΗΨΗ
ΑΛΕΞΑΝΔΡΕΙΟ ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ ΙΔΡΥΜΑ ΘΕΣΣΑΛΟΝΙΚΗΣ

Σχολή Τεχνολογικών Εφαρμογών | Μηχανολόγων Οχημάτων

Δεκέμβριος 2015 | Συνολικός αριθμός σελίδων: 89

Mika Lauren

Γεώργιος Ρόλης

ΠΕΙΡΑΜΑΤΙΚΗ ΜΕΛΕΤΗ ΕΝΟΣ ΕΠΙ ΠΑΝΤΟΣ ΕΔΑΦΟΥΣ ΚΙΝΗΤΗΡΑ ΑΝΑΦΟΡΙΚΑ ΜΕ ΕΚΠΟΜΠΕΣ ΚΑΥΣΑΕΡΙΩΝ ΚΑΙ ΣΩΜΑΤΙΔΙΩΝ ΜΕΣΩ ΔΙΑΦΟΡΕΤΙΚΩΝ ΣΥΣΤΗΜΑΤΩΝ ΜΕΤΕΠΕΞΕΡΓΑΣΙΑΣ ΤΩΝ ΚΑΥΣΑΕΡΙΩΝ

Η παρούσα πτυχιακή εργασία παρουσιάζει ένα πρόγραμμα μετρήσεων του ερευνητικού προγράμματος <<HERE PROJECT>> το οποίο έλαβε μέρος κατά την διάρκεια της άνοιξης του 2015. Συγκεκριμένα, η εργασία αυτή εξετάζει διάφορα συστήματα μέτρησης σωματιδιακών ρύπων που χρησιμοποιήθηκαν από το Turku University of Applied Sciences και άλλους συνεργάτες του ερευνητικού προγράμματος. Επιπλέον, σκοπός της παρούσας είναι η έρευνα των σωματιδιακών ρύπων ενός κινητήρα εσωτερικής καύσης και η μελέτη νέων μεθόδων για την ανάλυση των εν λόγω ρύπων καθώς και η ανεύρεση στοιχείων που θα μπορούσαν να επηρεάσουν τη νομοθεσία για την εκπομπή ρύπων.

Επί της ουσίας, η παρούσα πτυχιακή εργασία αποτελείται από δύο μέρη: τη θεωρία και την μέτρηση και ανάλυση δεδομένων. Στο πρώτο μέρος γίνεται μια ανασκόπηση της νομοθεσίας για την μέτρηση σωματιδιακών ρύπων σε μηχανές εσωτερικής καύσης καθώς και μια μικρή εισαγωγή αναφορικά με τα κοινά συστήματα ανάλυσης σωματιδιακών ρύπων. Στο πειραματικό (δεύτερο) μέρος αναλύονται τα δεδομένα απόδοσης του κινητήρα και των εκπομπών αέριων μέσω δοκιμών που έγιναν με δυναμόμετρο και παρουσιάζονται γραφήματα με τα αποτελέσματα αυτά.

CONTENT

APPENDICES

PICTURES

FIGURES

TABLES

LIST OF ABBREVIATIONS

Adblue	AdBlue is the registered trademark for AUS32, or Aqueous Urea Solution 32.5% that is used with the Selective Catalytic Reduction system (SCR) to reduce emissions of oxides of nitrogen from the exhaust of diesel vehicles
Approx.	Approximately
AT	Aftertreatment
CO	Carbon oxide
CO_2	Carbon dioxide
DFO	Diesel fuel oil
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EU	European Union
FMI	Finnish Meteorological Institute
fSCR	SCR on Filter
FSN	Filter smoke number
GDI	Gasoline direct injection
HC	Hydrocarbons
HDV	Heavy-duty vehicles
HERE	Health relevant and energy efficient regulation of exhaust particle emissions
ISO-8178-C1	International standard for exhaust emission measurement from a number of non-road engine applications
LDV	Light duty vehicles
M1	Mode 1

M7	Mode 7
N_2	Nitrogen
NH_3	Ammonia
NO	Nitrogen oxide
NO_x	Nitrogen oxides
NRSC	Non-Road Steady Cycle
O_3	Ozone
OEM	Original equipment manufacturer
PM	Particulate matter
SCR	Selective catalytic reduction
Set A	DOC + fSCR + SCR88
Set B	DOC + DPF + SCR89
TUAS	Turku University of Applied Sciences
TUT	Tampere University of Technology
US	United States
VOC	Volatile organic compound

1 DIESEL ENGINE POLLUTANTS AND PARTICULATE MEASUREMENT

1.1 Introduction

With the continuous development and greater exploitation of combustion engines, their environmental impacts have become more significant. For this reason some limits based on legislation should be placed to limit their environmental impact. In the automotive industry and other applications of combustion engines, new technologies are continuously introduced for emission reduction.

Due to the tendency of ever tightening permitted limits, manufacturers are continuously forced to seek more active and reliable solutions for exhaust aftertreatment systems. The soot particles (PM) together with nitrogen oxides (NO_x), are the most harmful internal combustion engine pollutants, thus they have become the focus of much research.

In the first steps of strengthening emissions legislation, it has already been imposed upon manufacturers of diesel engines to use a soot filter (DPF). In large industrial applications, the selective catalytic reduction (SCR) to reduce nitrogen oxides (NO_x) is used and this is the case nowadays also in many heavy vehicles, transportation, agricultural and even in many smaller cars.

Related with fossil fuel burning, particulate matter (PM) has caused great interest due to its effects on human health and the environment. Diesel engines are one of the major sources of PM, since there is a strong association between PM with carcinogenesis and problems of the respiratory and circulatory system (EPA, 2002). Hence, PM is subject to legal restrictions.

The contribution of vehicles to air pollution due to gaseous and particulate pollutants emitted from exhaust pipes is known and documented. During the last 20 years, the global automotive industry has faced constant challenges to find solutions to reduce emissions of pollutants such as nitrogen oxides, NO_x, carbon monoxide, CO, hydrocarbons, HC, particles (mostly nanoscale) but also carbon dioxide, CO_2, a gas that contributes to global warming.

The control of particulate emissions is achieved by reducing both the solid particles (soot) and liquid particles (droplets) formed from condensation of the exhaust gas when cooled. The latter may be sufficiently reduced by setting precursors, for example reducing sulfur in fuel and installing advanced diesel oxidizing catalysts for the oxidation of emissions of hydrocarbons, HC. The solid particles are connected with the nature of the diesel engine combustion process, and waste reduction can be achieved either by improving the combustion process in the engine or by applying aftertreatment systems like soot particle filters (Diesel Particulate Filters, DPF).

Advanced fuel injection systems in combination with the inherent high efficiency of diesel engines have led to the increase in diesel vehicle market share in Europe (already holds 51% of the market while in some countries more than 65%). This trend seems to continue - the emissions of diesel engines are able to meet the emission limits stipulated by law, which in the future will be more stringent. This is dependent on the successful development of economic, advanced soot particle emission control systems and oxides of nitrogen (NO_x). The harmful health effects of nanoparticles produced by combustion, such as soot particles, generate debates, resulting in the role of aerosol scientists becoming very important both for the evaluation of clean technologies and for the need to find solutions.

1.2 Pollutants of Diesel Engines

The diesel engine is a type of internal combustion engine in which the ignition is caused by the high temperature developed by the very high compression of the gas (adiabatic), unlike the gasoline engine in which the ignition is caused by sparks. Diesel engines are manufactured in two stroke and four stroke versions (Abdul – Khalek et al., 1998, pp.2-3).

The diesel engine has greater thermal efficiency than the existing internal and external combustion engines due to the very high compression and combustion inherent inclination, which allows to remove heat from the excess gas. The low speed diesel engines such as those used on ships and in situations where the weight of the machine is not considered significant have an efficiency of over 50% (two-stroke engines) (Oladipo et al., 2008, pp.4).

The invention of the diesel engine is assigned to the German Rudolf Diesel in 1893, although high compression engines existed before that time. However, they were not

large enough to cause the ignition of the fuel. The first operational diesel engine was built in 1897. In the beginning, diesel engines replaced the stationary locomotives. In early 1910, they were used in submarines and ships and later in trains, trucks and power plants. After the 1930s, they spread to use in cars.

Diesel engines emit the following pollutants (Dieselnet, 2015):

- Unburned hydrocarbons (HC)
    - Unburnt hydrocarbons are produced by the incomplete combustion of fuel or when they escape from the oil pan (sump) of the engine. This aldehyde hydrocarbon, may be combined with oxygen. According to laboratory studies, these compounds react in the presence of ultraviolet radiation and irritate human eyes, pollute the atmosphere and cause adverse effects on vegetation. They are also responsible for photochemical smog and some of these (particularly benzene) are carcinogenic.
- Oxides of nitrogen (NO_x)
    - Oxides of nitrogen are one of the key factors of the creation of photochemical smog. Nitrogen oxides under the influence of solar radiation are involved in certain chemical reactions, which result in the conversion of unburned hydrocarbons in photochemical oxidants and ozone production – also toxic to the respiratory system. Combining ozone, atmospheric oxygen and nitrogen oxides create a cycle of secondary pollution, which under favorable weather conditions results in the formation of photochemical smog.
- Carbon monoxide (CO):
    - Carbon monoxide is produced mainly from gasoline. It is a key product of incomplete combustion of hydrocarbons (and carbon generally) and when its concentration in air exceeds a certain level, they cause headaches and problems in the circulatory system. At very high levels (which can, however, be only indoors) they may prove even fatal. CO, however, is an unstable compound and when placed in the open air it is rapidly converted into harmless carbon dioxide, which means that it has only a local effect.
- Smoke:
    - Smoke is mainly produced from diesel engines (Diesel). The tinge of Diesel engine exhaust is normally visible in most large loads due to

particulate emissions. So, based on the hue, the smoke exhaust categorized emissions are as follows:

- White Smoke, is the one consisting of fog liquid (i.e., condensed water) and unburned fuel particles and occurs during cold start.
- Blue smoke, consisting of unburned particles liquid lubricating oil fog, makes its appearance when there is a problem with the lubrication (e.g. worn or stuck piston rings)
- Black smoke or "Press Soot" smoke, consisting mainly of thin solid unburned carbon particles (carbonaceous material), i.e. soot generated by local pyrolysis (otherwise cracking) of the fuel in areas with relative oxygen deficiency, makes its appearance in high load areas (i.e.,> 85% of the maximum).

Contaminants from vehicle engines are formed due to cleavage (chemical) products of combustion because of the high temperatures involved in the combustion chamber, which can locally reach even 3000 K (2726 ℃). The products of combustion, if combustion is perfect, are given by the following chemical reaction equation, which of course has only a qualitative value, as there are no stoichiometric factors (Xatzimanolakis, 2011, pp.34-38):

$$C_nH_m + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2 + O_2$$

Practically, however, the products of perfect combustion undergo dissociation, having the consequence that the following radicals and compounds in the products are displayed (Pandazakis, 2014, pp. 8-11):

$H_2O, H_2, O_2, N_2, N, O, OH, H, CO, CO_2, NO, HC,$ etc.

In addition, the products of perfect combustion can also be aldehydes, ketones, O_3, etc. From these gaseous pollutants, the most basic is NO_x, CO and HC referred to above. Their concentration level in the exhaust gas export piston engines is legislated in many EU countries, as well as in the USA and Japan, which follow standard devices and measurement methods. These three main air pollutants appear in both categories of piston engines, namely Diesel and Otto, but have significant differences in their concentration in the exhaust gas export. The particles emitted by Diesel engines are those of carbon black (soot), while the soot emissions from Otto engines are almost nil, with the exception of Otto gasoline direct injection engines (GDI). In addition to these,

there are other pollutants that are formed under the influence of solar radiation on primary pollutants. These pollutants, such as ozone (O_3), are called secondary pollutants (Hall, 2003).

1.3 Particulate Emissions in Diesel Engines

The evolution of the last 20 years in the technology of diesel vehicles has reduced the levels of pollutants by 5-10 times compared to mid-80's levels. The following Figure 1.1 shows how European legislation contributed to limit emissions of particulates since 1992 (Dieselnet, 2015).

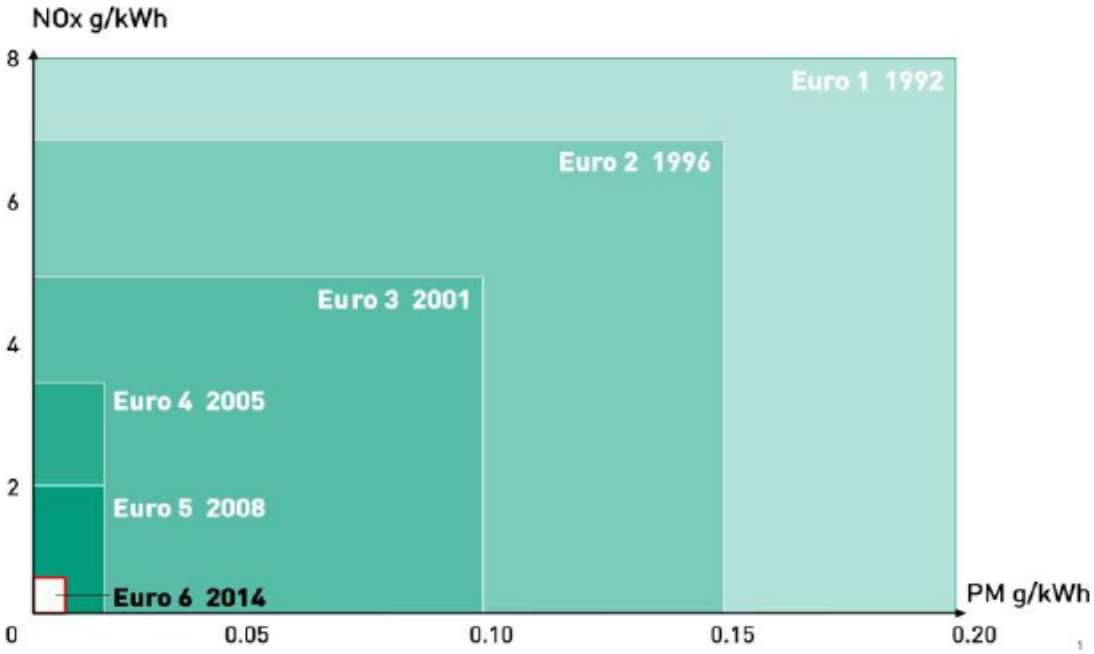


Figure 1.1. Reduction of the microparticles [PM], & [NO_x] on diesel vehicles and the contribution of European legislation (Pandazakis, 2014, pp. 12).

The particles of oil combustion are composed mainly of carbonaceous material (soot) produced in combustion, which have absorbed some components. The particles are distributed in a wide range of sizes from 20 nm to 10 microns, which makes them breathable. They are divided into soluble and insoluble organic fractions, which are used as soot estimates. The rate of soot particles from the extraction of a Diesel engine is different, although it is normally higher than 40-50%. Other compounds contained in the particles are unburned fuel or lubricant engine oil by partial combustion, metal debris from wear and salts derived from fuels. Composition of the particles emitted by a Diesel engine during transient cycle is presented in Figure 1.2(Johnson, 2004, pp.7-9).

The fraction of sulfuric acid and salts is proportional to the sulfur content of the fuel. The fraction of unburnt fuel / engine oil (soluble organic fraction) differs depending on the engine design and operating conditions. The range extends from 10% to over 90%. Soot is generated by unburned fuel, and this fuel forms particles from the gas to solid phase when the fuel is rich with high temperatures. Hydrocarbons or other existing molecules are condensed or absorbed by soot, depending on the ambient conditions (Johnson, 2004, pp.11-12).

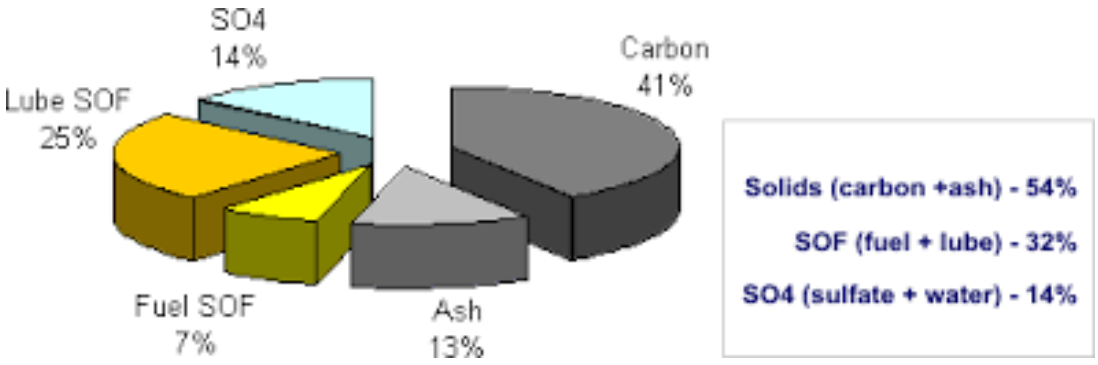


Figure 1.2. Composition of particles emitted by a Diesel engine during the transient cycle (Dieselnet, 2015).

The evolution of the liquid or gas phase of hydrocarbons in solid soot particles includes six procedures (Particle Measurement Programme, 2003, pp.4-5):

- Pyrolysis: endothermic process that alters the molecular structure of fuel in the presence of high temperature and produces components such as polycyclic aromatic hydrocarbons, the precursor of soot.
- Nucleation: is the nucleation of nanoparticles or unstable materials such as hydrocarbons.
- Surface growth: mass added to the surface of a carbon black particle.
- Coagulation: violent clashes of spherical particles to join together to form larger spherical particles.
- Agglomeration: the particles remain joined to form large groups in the chain structure.
- Oxidation: happens in every stage of the process, especially at temperatures above 1300 K (approx. 1000 ℃), where soot is burned with oxidants and gaseous products are formed such as CO, CO_2 and H_2O.

1.3.1 Distribution of PM size

The regulations for particulate emissions are based on the mass of emitted particles. Nevertheless, the size distribution of the particles raises interest in terms of the quality of the air, as it is considered that toxicity increases as particle size decreases. Soot particles of 100 nm affect the health of humans and have dimensions so small that they can be absorbed through the nasal mucosa and they are large enough to manage to deposit in the lungs (Vouitsis et. al., 2003, pp. 635–672). Unlike the mass, the number of particles is not retained. Inside the exhaust tube of a Diesel engine, conditions are constantly changing and may lead to the formation of particles (therefore increasing the number of particles and the concentration of the mass), but also on concentration and coagulation (i.e. to reduce the concentration and to increase the size of the particles). These phenomena also occur during dissolution and sampling, preventing us from drawing clear conclusions and designing a report template.

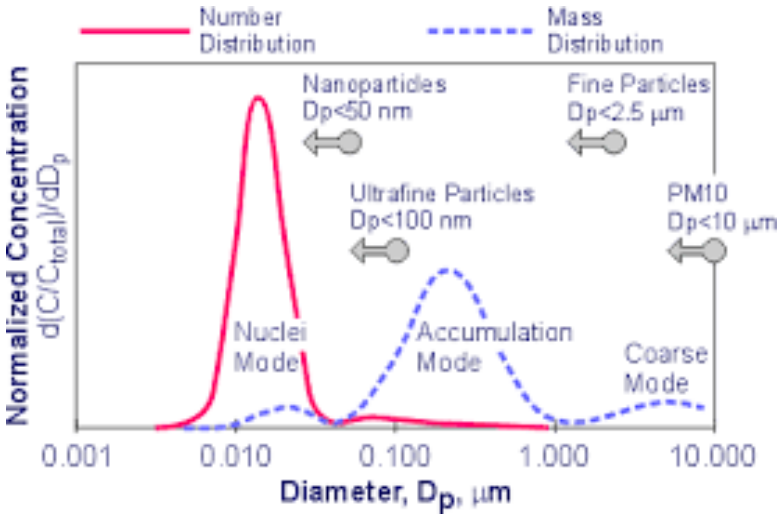


Figure 1.3. Typical size distribution of particles in diesel engine (Pantazakis, 2014, pp.15).

Figure 1.3 shows an idealized logarithmic distribution of the number and mass of the particles in a Diesel engine exhaust, depending on the diameter of the particles. The concentration of particles in any range, as far as the size is concerned, is proportional to the area under the curve corresponding to this range. The greater mass of particles is called the accumulation mode for the range of diameters of 0.1 - 0.3 microns. There are carbonated aggregates and related adsorbed materials. The nanoparticle state (nuclei

mode) consists of particles with diameter range of 0.005 - 0.05 micrometers. VOC hydrocarbons, sulfur and solid compounds of carbon and metals are often contained in this diameter range. Over 90% of the particles emitted from a Diesel engine fall in the nanoparticle state (nuclei mode), although it contains only 1-20% of the mass of particles. The "coarse" mode (coarse mode) comprises 5 - 20% of the mass of the particles. The particles of the accumulation phase have deposited inside the surface of the cylinders and the exhaust manifold. Furthermore, some size ranges are shown for the atmospheric particles: PM10 with Dp (diameter) <10 microns, fine particles (fine particles), Dp <2.5 microns, very fine particles (ultrafine particles), Dp <0.10 microns and nano-particles (nanoparticles), Dp <0,05 microns (Vaaraslahti et. al., 2004, pp. 4884-4890).

The particle size is influenced by the way engine emissions affect the environment in the following ways: by affecting the residence time of particles in the atmosphere, by the optical properties of the particles and by the surface of particles and their health effects. The length of time that particles remain in the atmosphere is greater for particles with a diameter of 0.1 - 10 microns, ranging in a week. Larger particles are removed from the atmosphere rapidly by accretion, while smaller with diffusion and pelleting. An average residence time for the particles with a diameter of 10 nm is about 15 minutes (Vouitsis et al., 2003, pp. 635-672). For removal of these tiny particles pelleting is usually applied in the accumulation phase. While in permanent operation, the particles of the accumulation phase are formed (80 - 110 nm). At the start of combustion, the majority of the particles is between 80 - 90 nm, and then, carbon black particles are agglomerated to form larger diameter particles. While the oxidation of soot is realized, particle number is drastically decreased in the entire range of sizes (Vaaraslahti et. al., 2004, pp. 4884-4890). As the load increases, more fuel is injected and larger particles are formed, while nano-particles are favored during idling ("idle"). Figure 1.4 shows the variation of the emitted particles in relation to the equivalent ratio of fuel-air F (i.e. the load) pointing the corresponding change of NO and CO for Diesel engine of direct injection, the soot is formed due to the load increase (Pantazakis,2014).

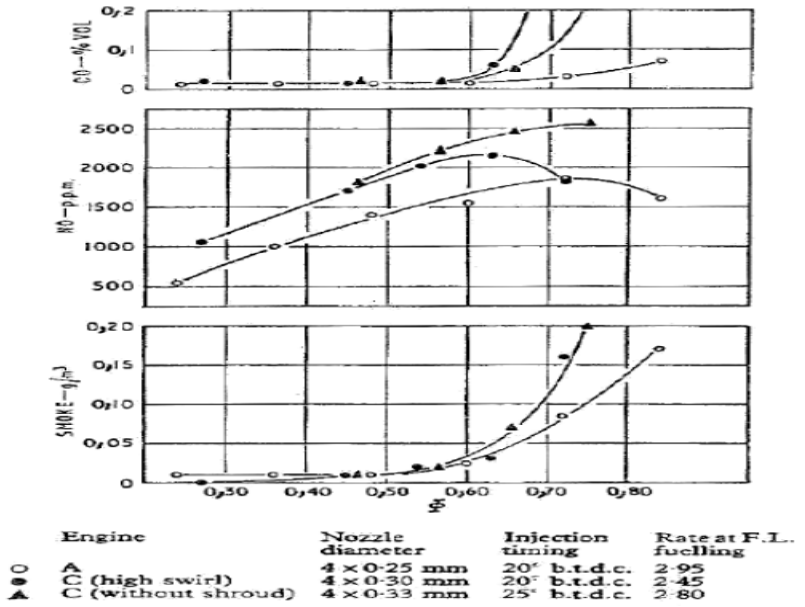


Figure 1.4. Change of emitted particles as a function of the ratio F (Pantazakis, 2014, pp.16).

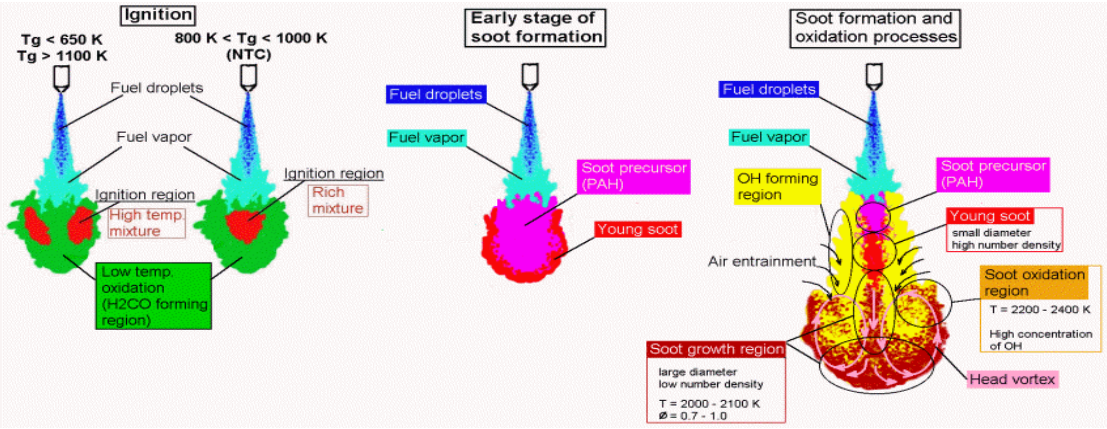


Figure 1.5. Forming regions and oxidation of soot (Pantazakis, 2014, pp.8-9).

Figure 1.5 shows the forming and oxidation regions of soot, and the forming zone of nitric oxide around the flame. Among the most important factors affecting the concentration of the number of particles and the size distribution is the fuel type. Preference is placed on fuels with very low sulfur content for reduced overall emissions of particles, although it has been observed that this increases the concentration of nano-particles. The same applies to higher fuel injection pressures or lower exhaust gas recirculation rates (Tobias, 2001, pp. 2233–2243).

1.4 PM Exhaust Characterization in Diesel Engines

There is no precise definition of the emitted PM by diesel engines. The definition is determined by the sampling method, which itself is an important part of legislation (Vouitsis et al., 2003, pp. 635–672). Legislation specifies transportation of the exhaust in the dilution duct, diluting with filtered air, isokinetic sampling and passing by a filter with temperature less than 52 ° C. The mass emission is determined by weighing the filter after stabilization in a special chamber. Based on sampling method according to regulations, the PM of gas comprises carbon particles which have undergone agglomeration and are adsorbed onto inorganic and organic compounds. A percentage of PM corresponds to metallic compounds.

It is obvious that any change in the process can give different results and standardization of the process is important in comparing data from different laboratories. Such standardization is only for mass measurement, thus intensive research is realized in order to investigate the standardization of sampling method measuring capabilities and other parameters (number, size, surface area) (Ntziacristos et al. 2003, Thompson et al. 2004, pp. 12).

Figure 1.6 shows the evolution of European legislation on PM emission limits relative to light duty diesel vehicles.

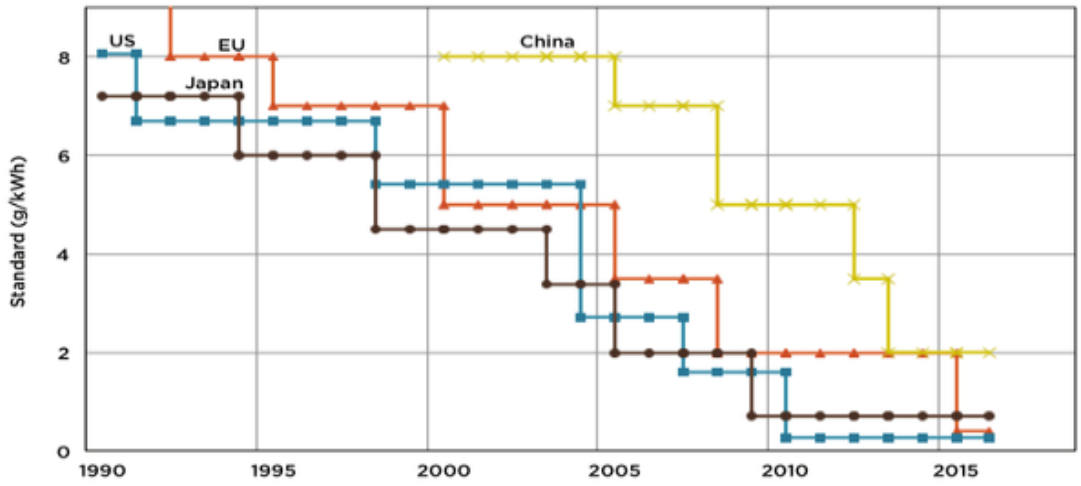


Figure 1.6. Evolution of European legislation on PM emission limits 1990-2015 (transportpolicy.net).

Based on experimental and not strictly standardized sampling-measuring methods, diesel vehicles can be defined asmixed particle systems with maximum numerical concentration in the core area (nucleation mode, average diameter of <30 nm) and the maximum mass concentration in the accumulation area (accumulation mode, median diameter = 30 - 100 nm) (Figure 1.7).

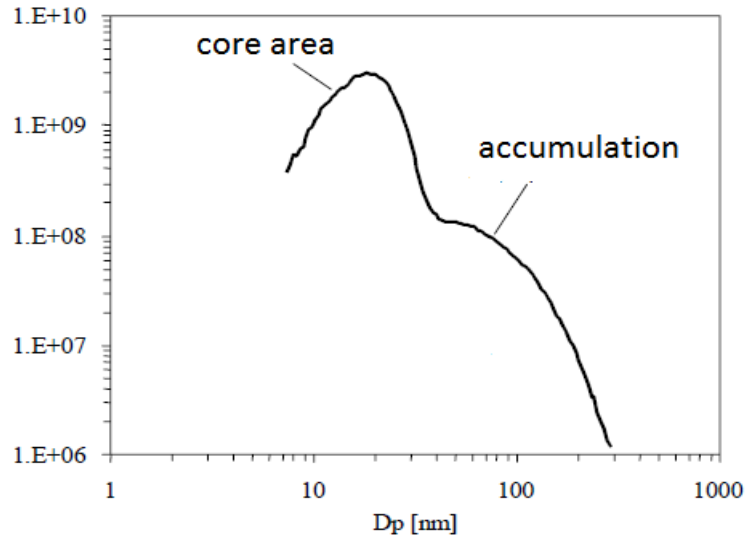


Figure 1.7. Size distribution of PM exhaust (dN/dlogDp) in passenger diesel vehicle (Euro I). Fuel: European diesel fuel specification EN-590 (sulfur content = 250 ppm). (Vouitsis et al. 2005, pp. 5).

The particles of the core region are referred to as nanoparticles, although the two terms are not identical .The nanoparticles are defined as particles with an average diameter of <50 nm (Pui and Chen, 1997, pp. 539-544), and include all of the particles of the core region and part of the particles accumulation. At present it is assumed that sulfuric acid together with water is condensed homogeneously, giving particle cores, and heterogeneously onto the carbon surface. Then, heavy hydrocarbons derived from oil and unburned fuel are condensed or adsorbed on the available liquid and the carbon surface, increasing the size of the liquid core and the carbonate particles and forming the organic fraction of PM (Vouitsis et al. 2005, pp. 3-21, Sakurai et al. 2003, pp. 1199-1210, Tobias et al. 2001, pp. 2233-2243). The contribution of the particles of the core region in the emitted particulate mass is low (less than 10%). Under certain conditions, the application of PM filters that reduce the emitted mass (with or without oxidant catalysts) may lead to an increase in the number of particles emitted due to the strengthening of nucleation hydrated sulfuric acid capacities (Figure 1.3). The oxidizing

catalyst may lead to a reduction of the mass of the volatile part of the PM and at the same time increase the overall numerical concentration by enhancing the oxidation of sulfur dioxide to sulfur trioxide and sulfuric acid. The use of reduced sulfur fuel makes the influence of the lubricant more significant (Vaaraslahti et al. 2004, pp. 4884-4890).

The particles of the accumulation region are substantially those set as PM from the legislation method. The adsorbed organic compounds from unburned fuel and oil and metal compounds originate mainly from the lubricant, without excluding the contribution of the machine due to wear. The organic fraction, according to the method of determination, is referred to either as a soluble organic fraction (organic solvent extraction) or as a volatile organic fraction (heating). The sulfuric acid, according to availability of base metal compounds (primarily fuel and lubricant) may form respectively sulfates (non-volatile). For metal compounds, homogeneous nuclei of the crystals volatile metal ash are assumed at the time of discharge, which coagulate and respond to the accumulation area. Of course, depending on the rate of aggregation, the metallic particles may be present in the core region. Note that the proportion of metal compounds is expected to increase in machines optimized to reduced carbon particles due to strengthening of capacities of homogeneous nucleation.

Figure 1.8. shows size distribution of PM exhaust in diesel passenger vehicles according to Euro III with and without PM filter.

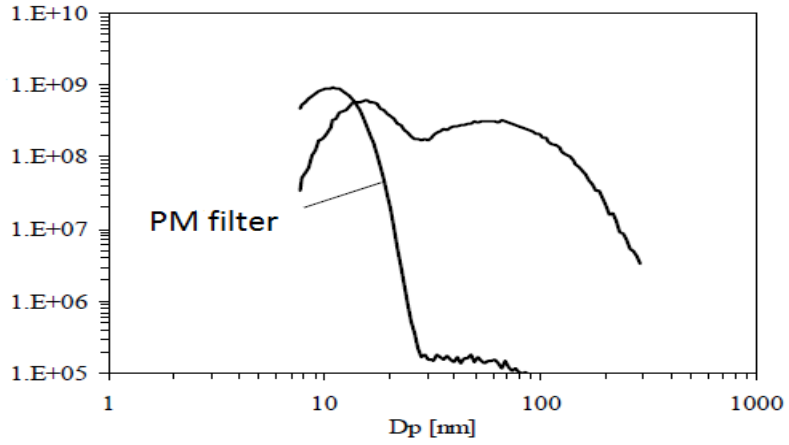


Figure 1.8. Size distribution of PM exhaust (dN/dlogDp) in diesel passenger vehicles (Euro III) with and without PM filter. Fuel: European diesel fuel specification EN-590 (sulfur content = 50 ppm). (Vouitsis et al. 2005, pp. 5).

1.5 Technologies for Reducing Pollutants in Diesel Engines

The most important technological development that has contributed remarkably to reducing greenhouse gas emissions over the last 15 years is the use of catalytic converters or simpler catalysts. The use of catalysts has been implemented effectively in cars sold in the EU with the application of emission standard "Euro II" in 1996. In retrospect, the European emission standards impose certain emission limits for the gasoline engines and not a specific technology. In practice, to achieve the highly demanding limits of 'Euro II' standard the use of catalysts was rather inescapable for all manufacturers, despite (or maybe because of) the fact that some of them were quite close to achieving those emission limits without resorting to the catalysts, e.g. with better combustion inside the combustion chamber (Dieselnet, 2015).

The **catalysts** are installed between the vehicle engine and the exhaust gas outlet pipe (exhaust). The catalysts are usually made of ceramic material and are celled and coated internally with noble metal, usually platinum (platinum), rhodium and / or palladium, which act as catalysts. The cellular form of converters is suitably designed to have a very large surface area relative to volume ratio. This way it ensures effective exhaust of chemical reactions with the metallic catalysts carried out only on the surface of the honeycomb shape of the catalytic converter (CRES, 2015, pp.8-9).

Modern gasoline engines are equipped with a "three-way catalyst" system, which reduces emissions of three gaseous pollutants: unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x). A three-way catalyst consists substantially of two different "parts": a reducing catalyst separates harmful nitric oxide NO into harmless nitrogen N_2 and oxygen O_2 [$2NO > N_2 + O_2$] and an oxidizing catalyst which oxidizes dangerous pollutants CO and HC and converts them into carbon dioxide CO_2 and water H_2O. CO_2 is a major problem as it is one of the gases that cause the greenhouse effect, however the amount of CO_2 produced by the oxidation of CO in engines is generally not considered significant.

Reducing catalysts can operate only when an engine is running near the "stoichiometric" ratio of the fuel mixture. Stoichiometric ratio is the proper ratio of air and fuel required to enter the cylinders of the engine to complete combustion of the mixture without excess air or fuel. To ensure the operation of gasoline near a stoichiometric fuel mixture, an electrochemical oxygen sensor ("lambda sensor") is installed in the exhaust of the vehicle after the catalyst (CRES, 2015, pp.8-9).

The "lambda" sensor is connected to the central control unit and analyzes the oxygen in the exhaust gases providing the appropriate data to the main unit, so the latter can adjust the amount of fuel injected in the cylinders.

Diesel engines are designed to operate with a "poor" mixture, which is operating constantly with excess air in relation to the stoichiometric mixture ratio. Reducing catalysts cannot operate in conditions of "poor" mix and for this reason diesel is equipped only with oxidizing catalysts. The oxidizing catalysts are effective in reducing emissions of HC and CO as well as part of the emissions of particulate matter (PM), but not to in reducing NO_x emissions. It is exactly for this reason that diesel engines have much higher NO_x emissions than gasoline (Sakurai, 2003, pp. 1199-1210).

The **exhaust gas recirculation** (EGR) is a technique used to reduce emissions of vehicle NO_x. For an understanding of the exhaust gas recirculation method it is important to note that as NO_x nitrogen oxides are formed at very high temperatures, they cause emissions of oxygen and nitrogen compounds in the atmosphere. The higher the temperature the greater the amount of nitrogen oxides produced (CRES, 2015, pp.9-10).

The engines with exhaust gas recirculation deflect the part of exhaust gases which have low oxygen content after the combustion back to the inlet of the engine. This decreases the temperature inside the engine, as there is now less oxygen for combustion. Thus, reducing the temperature attained inside the combustion chamber also reduces the rate of NO_x formation.

Exhaust gas recirculation was first introduced in the 70s in the US on gasoline vehicles before the use of three-way catalysts supplanted this technique. As explained above, the three-way catalysts are particularly effective in removing NO_x. In Europe, exhaust gas recirculation is used in almost all new cars and vans that run on petrol after the imposition of emission standard Euro II in 1996 (SMMT, 2015). Exhaust gas recirculation results in a small increase in fuel consumption. Therefore the automakers are reluctant to install recirculation systems in heavy vehicles and large trucks as the owners of such vehicles have a strong emphasis on minimizing fuel consumption. However, to comply with emissions of Euro IV standard of 2005, fuel recirculation should be installed in certain heavy vehicles (Pandazakis, 2014).

The **selective catalytic reduction** (SCR) is an even more effective technology for reducing NO_x emissions from diesel engines. In this method, use is made of a special catalytic converter which processes the exhaust gases of a Diesel engine and reduces

NO_X emissions, unlike the exhaust gas recirculation, which aims to reduce the NO_X formation (CRES, 2015, pp.10-11). In selective catalytic reduction, before the introduction of the exhaust of the diesel engine in the SCR catalyst, ammonia or urea is sprayed (NH_3) so that the ammonia can react with carbon monoxide and nitrogen dioxide (NO and NO_2) and harmless nitrogen N_2 and water H_2O are produced (Pandazakis, 2014). [$4NO + 4NH_3 + O_2 = 4N_2 + 6H_2O$].

The selective catalytic reduction is a commercially mature technology already applied to large stationary Diesel engines where the size and weight of the engine is not a primary factor (marine engines, power plants, etc.) as well as some heavy Diesel engines. This method has spread widely from 2006 onwards in order to ensure compliance of heavy vehicles and trucks with the stringent NO_x emissions limits of European standards Euro IV and V (CRES, 2015, pp.9-10).

Diesel Particulate filters (DPFs) filter and remove particulates (PM) from vehicle exhausts. They are very effective and often remove more than 90% of the particles contained in the exhaust gas (CRES, 2015, pp.11). The particles are collected in the form of soot which is subsequently removed by thermal regeneration (or simply burning) to prevent malfunction of the filter i.e. in a clogged filter the soot is burned to regenerate it (Ntziachristos et al., 2003, pp.3-4).

The exhaust gas temperature of the Diesel engines is not so high to "burn" directly the soot, but the particle filters circumvent this problem in one of two ways: The "passive" particle filters use oxidizing catalysts to reduce soot oxidation temperature while the "active" particle filters periodically increase the temperature at the appropriate level. The most common methods for increasing the temperature in an active system is either through periodic combustion of extra quantity of petroleum to heat the evaporation, or by some form of heating by electricity (Majiewski, 2005).

Diesel particulate filters are currently in use by only a minority of new vehicles but their use is continually becoming more frequent and some European countries provide incentives and subsidies for the installation of particulate filters. Moreover, it is commonly believed that particulate filters must be included in the basic equipment of vehicles as they are effective and generally cheap. Standard particulate emission limits of Euro V make it mandatory to use particle filters Diesel. Retrofitting existing vehicles so that they can use particle filters Diesel is complex and usually done only on heavy vehicles (Dieselnet, 2015).

To comply with the current US and EU emission specifications, implementation of aftertreatment is recommended, based on either particulate matter (PM) or nitrogen oxides (NO_x). Deployment of aftertreatment allows for the engine to widen the power output, altitude capabilities and transient efficiency quality. Exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) are available in the current diesel engine market. The choice between EGR and SCR for NO_x reduction depends on the original equipment manufacturers (OEM's) production historical past, technology experience, consumer necessities and long run product approach. Engines with EGR are only diesel based and frequently require a DPF. DPF active regenerations imply that the highest temperatures of the aftertreatment system and tailpipe exhaust gases must be confined by means of the exhaust approach design (Majiewski, 2005).

1.5.1 DPF and Soot-traps

Diesel Particulate Filters, (DPF) or soot traps, or soot filters (soot filters) are essentially filters that contain the particles of carbon black and then they oxidize them (Figure 1.9.). These traps are placed in the exhaust pipe through which the hot exhaust gases are circulated. The first soot filters were used in 1985 in Mercedes-Benz vehicles, but were withdrawn from the market due to problems. Their use was limited later in applications of "off road" and industrial uses until the 1990s, when some retrofitting programs for heavy vehicles began (heavy-duty vehicles, HDV). Today, soot filters are used in most light duty passenger cars (Light Duty Vehicles, LDV) in Europe, the USA and Japan (SMMT, 2015). They are also used frequently and in trucks. The Euro 4 emissions standards for passenger vehicles, which has been in force since 2005, has set soot particle emission limits which manufacturers can comply with without the use of soot filters and only with internal measures. In Figure 1.9 there is an example of a soot trap (Majiewski, 2001).

The new Euro 5 emission limits applicable from 2009 set out a very significant reduction on the mass of emitted soot particles (Particulate Matter, PM) of 25 mg / km to 4.5 mg / km. There is an additional limit on the number of particles emitted in 6 × 1011 particles / km. The measurement of particle number is the PMP process, and this limit is considered quite low (Majiewski, 2001).

Figure 1.9. Soot trap example (Pandazakis, 2014, pp. 25).

Soot-traps are effectively membranes that are associated in the export of exhaust gases and are intended to collect the carbon black particles and their subsequent oxidation. The filters used nowadays in automotive diesel engines have efficiencies ranging from 85% in cases of "Full load machine" to even approaching 100%. When the concentration of particles in the filter exceeds a certain threshold, the rebirth mechanism is activated (filter regeneration) by increasing the exhaust temperature or through the production of nitrogen oxides NO_x, burns and oxidizes respective particles of soot and thus obstructs the filter allowing it to continue operating. Figure 1.10 shows a Soot filter with the input and output components of the system (Majiewski, 2001).

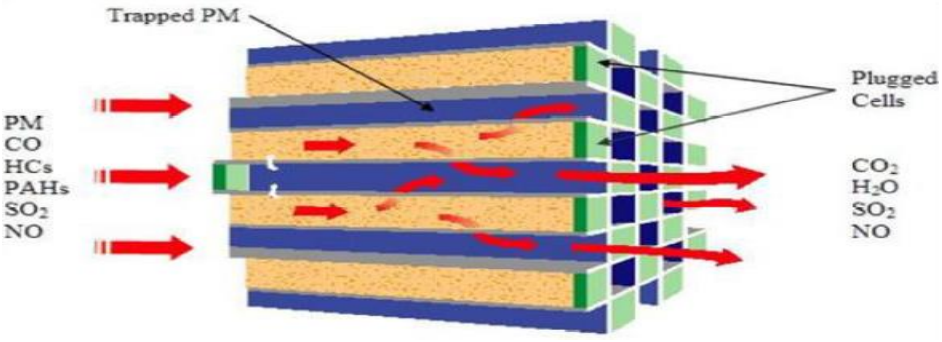


Figure 1.10. Soot filter with the input and output components of the system (Pandazakis, 2014, pp. 27).

1.5.2 EGR

The EGR method (Exhaust Gas Recirculation) is a method used in gas and diesel engines, aimed to reduce emissions of nitrogen oxides (NO_x's). Figure 1.11 shows EGR

exhaust gas recirculation in a diesel engine. Although there are several variations and modifications of the EGR devices (for example several old techniques which due to the modern requirements for the reduction of NO_x emissions gained some interest), the standard mode is the recirculation of exhaust gases from the combustion chamber in the intake valves (PARTICULATES, 2000).

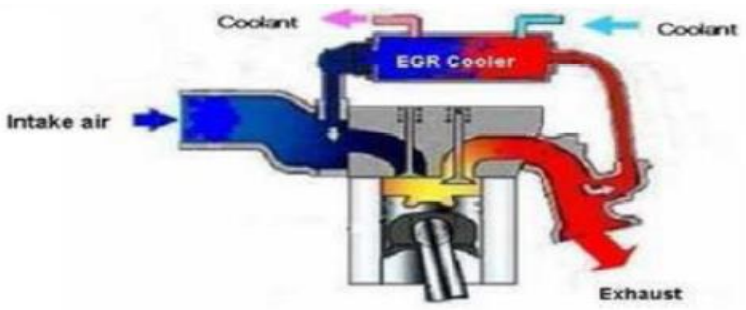


Figure 1.11. EGR exhaust gas recirculation in a diesel engine (Xatzimanolakis, 2011, pp.42).

NO_x emissions are reduced due to the reduction in the percentage of oxygen in the air intake flow to the combustion chamber by increasing the heat capacity of the fuel mixture. The direct effect is the increase in specific fuel consumption and the increase in soot emissions.

1.5.3 SCR (Selective Catalytic Reduction)

SCR process (Selective Catalytic Reduction) is a method of converting hazardous nitrogen oxides (NO_x), emitted from diesel engines, through a catalytic reaction of nitrogen and water. The efficiency of this device is quite high (close to 95%) and makes the specific method one of the most widespread. Mixing exhaust gas with ammonia (essentially water-urea solution) is the characteristic point of this method (Majiewski, 2005). An SCR system is constituted as shown in Figure 1.12, by a urea injector (urea injector) and an oxidation catalyst (oxidation catalyst).

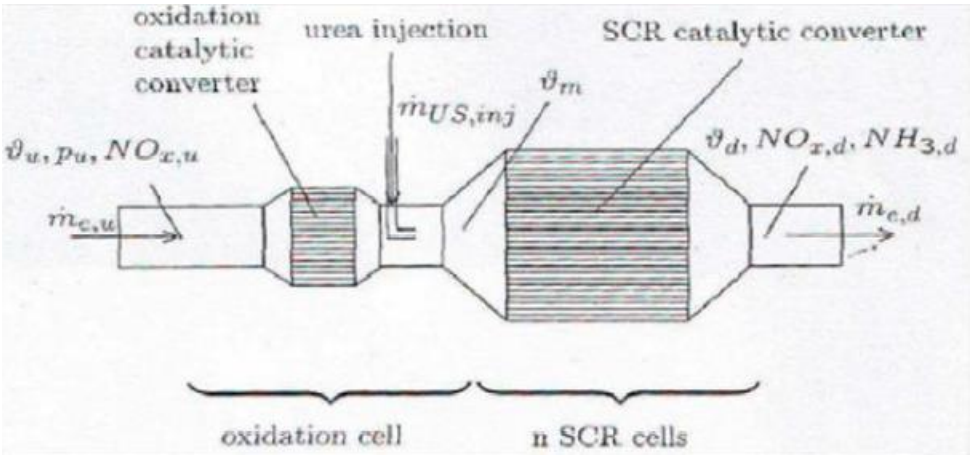


Figure 1.12. SCR system with two catalytic converters and urea injector (Xatzimanolakis, 2011, pp.40)

In this method a specific catalytic converter is used which processes the exhaust gases of the Diesel engine and reduces NO_x emissions, unlike the exhaust gas recirculation (EGR) which aims to reduce the formation of NO_x within the cylinder. In a selective catalytic reduction, before the introduction of the exhaust of the diesel engine in the SCR catalyst, ammonia is typically injected in solution form (urea) so that the ammonia can react with carbon monoxide and nitrogen dioxide (NO and NO_2), in order to produce innocuous nitrogen (N_2) and water vapor (H_2O). This method has spread since 2006 for compliance of heavy vehicles with the stringent NO_x emission limits of European standards Euro IV and V. Selective catalytic reduction is a commercially mature technology already applied in large naval or industrial Diesel motors, where size and weight of the engine is not a primary factor (Majiewski, 2005).

The advantages of the method are a) high efficiency on the reduction of NO_x to N_2, which can reach 90%, b) the applicability in flue gas containing particulate matter, and c) the common catalysts used of vanadium / titanium type are not inactivated by SO_2 and H_2O contained in the feed. It can also reduce the consumption of oil up to 5% compared to alternative technologies which optimize the functioning of the engine in order to reduce consumption. In addition, there is the advantage of ease of maintenance as it is not necessary to have a soot particle filter as in the exhaust gas recirculation method. Certainly, for more efficient pollution abatement, a soot trap is more commonly used. However it comes with many drawbacks such as high installation costs, high costs of ammonia and catalysts and toxicity of ammonia that escapes into the environment and causes additional problems (Hall and Colin, 2003).

The most prevalent catalysts in commercial application today are the vanadium catalyst (V) in the presence of titanium carrier and other metal oxides such as tungsten (W), molybdenum (Mo), manganese (Mn), antimony (Sb). Specifically, vanadium pentoxide is used (V_2O_5). The V_2O_5 is the final product of the oxidation of metallic vanadium, the metal ammonium and lower oxides of vanadium. When it is pure, it has orange color (Figure 1.13.) and is slightly soluble in water. Vanadium Catalysts based on titanium dioxide (TiO_2) show high activity and selectivity for reduction of NO_x with a reductant NH_3 and resistance to SO_2 poisoning (Majiewski, 2005). Figure 1.13 shows a catalyst of vanadium pentoxide.

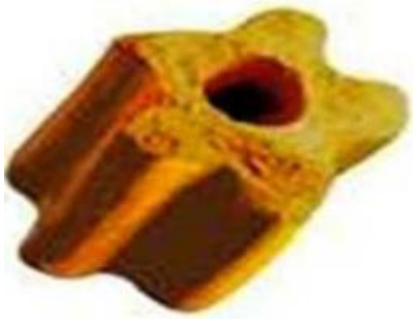


Figure 1.13. Catalyst of vanadium pentoxide (V_2O_5) (Pandazakis, 2014, pp. 40).

These catalysts have relatively high surface area, are active in a broad temperature range and highly stable with time in the presence of SO_2 and H_2O. Water is adsorbed very weakly to the surface of the catalyst and does not hinder the adsorption of ammonia and the SO_2 covers a very small part of the active centers of the catalyst at operating conditions, while the catalyst remains active for the reduction of NO_x by ammonia and the catalytic conversion of SO_2 to SO_3. The increased activity of these catalysts is connected to the compatibility of the crystal structure of titanium with vanadium pentoxide. Significant enhancement of the catalytic activity of V_2O_5 / TiO_2 is observed by the presence of another oxide such as Nb_2O_3, chromium oxide (Cr_2O_3), phosphorus oxide (P_2O_5), and WO_3, the surface of V_2O_5. The tungsten oxide (WO_3) significantly enhances the catalytic activity of V_2O_5, even when deposited on aluminum oxide or zirconium. However, the main problem that arises with the use of vanadium is malfunctioning at temperatures higher than 600 ° C, making the use of the SCR process in conjunction with a soot trap problematic due to the fact that in the soot traps the

thermal regeneration in the active systems is achieved by increasing the temperature exhaust (Oladito et al., 2008, pp.6).

1.5.4 Diesel Oxidation Catalyst (DOC)

In chemistry, a catalytic converter is a substance that accelerates a chemical process without being affected itself. Catalytic converters are used in diesel and gasoline vehicles with characteristic differences in the way they operate and are adjusted between the combustion chamber and final extraction of exhaust (Abdul – Khalek, 1998, pp.2-3). The modern version of the catalyst for gas vehicles is the three-way catalyst that oxidizes carbon monoxide (CO) and hydrocarbons (HC) and reduces nitrogen oxides (NO_x) into nitrogen (N_2).

Respectively the catalysts used in diesel vehicles mainly use oxidation reactions (Diesel oxidation catalyst - DOC). These catalysts use oxygen to convert CO to CO_2 and hydrocarbons into water and CO_2 (Thompson, 2004, pp.5). The specific catalytic converters are characterized by efficiencies that reach 90% and are also quite effective in reducing soot emissions. Their disadvantage is that they cannot prevent the emission of NO_x's. In order to reduce also NO_x emissions, they are often combined with SCR-EGR techniques presented in previous paragraphs. Figure 1.14. shows a catalytic oxidation converter with input and output products.

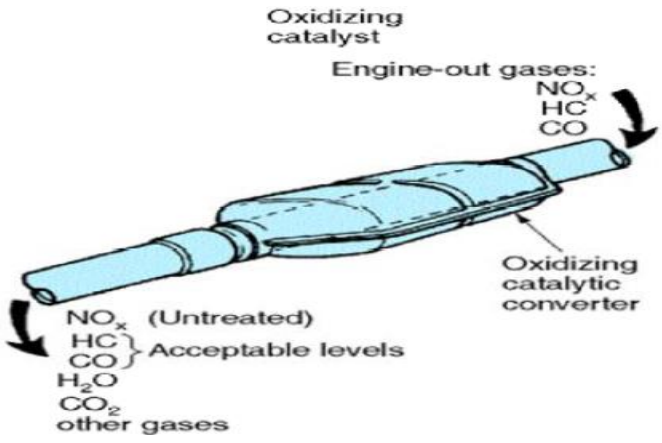


Figure 1.14. Catalytic oxidation converter with input and output products (Xatzimanolakis, 2011, pp. 43).

2 RESEARCH PROGRAM AND FACILITIES

2.1 Facilities

The present research program was conducted in the Engine Research Laboratory at Turku University of Applied Sciences. The research was performed with a prototype Agco Power 49 AWF diesel engine with prototype engine software.

The infrastructure for the particular research engine consisted of a Schenck W 400 eddy-current dynamometer, having transient capability. The analytical capabilities include ISO 8178 compliant measurements for gaseous emission components and PM. The instrumentation used to measure the several variables under investigation is presented in Table 2.1 below.

Table 2.1. Instrumentation of exhaust emission measurement.

Emission	Instrument	Operation principle
NO, NO_2	Eco Physics CLD EL ht 700	Chemiluminescence Detector (CLD)
THC	CAI HFID 300	Flame Ionization Detector (FID)
CO, CO_2	Servomex Xentra 4900	Non-dispersive Infrared (NDIR)
O_2		Paramagnetic Sensor
Smoke	AVL 415 S Smoke meter	Measurement of filter paper blackening. Filter Smoke Number (FSN)
	Dekati PM10 (as a filter holder)	Impactor
	ABB Sensyflow P thermal mass flowmeters	Intake air mass flow
	Micro Motion CMF025M Coriolis mass flow meter	Fuel mass flow
	Pegasor M –sensor	Particulate mass (PPS)

Several other instruments were also used during the campaign from other project partners like TUT, FMI and Dekati. These results were not reported in this thesis.

2.2 Fuel and Lubrication

The fuel was ordinary diesel fuel oil (DFO). The required maximum Sulphur content was 10 ppm and only one fuel batch was used during the study. The analyses for the used fuel batch are shown in Table 2.2. The particular diesel fuel oil is supplied by the Neste Corporation. The fuel complies with the EN 590:2013 standard.

Table 2.2. The fuel analysis.

Feature	Method	Unit	Sample DFO_031
Density 15 ° C	ENISO12185	kg/m3	842,3
Ash 775 ° C from oil products	ENISO6245	wt-%	< 0,001
Cetane number on engine	ENISO5165		52,4
Monoaromatics	EN12916	wt-%	25,1
Diaromatics	EN12916	wt-%	3,6
Tri + aromatics	EN12916	wt-%	0,35
Polyaromatics	EN12916	wt-%	3,9
Aromatics	EN12916	wt-%	29,0
Caloric value, on calorimeter	ASTMD4809	MJ/kg	45,787
Total nitrogen, oil products	ASTMD4629	mg/l	15
Carbon, C, from oil products	ASTMD5291	wt-%	85,9
Hydrogen, H, from oil products	ASTMD5291	wt-%	13,3
Effective caloric value (hydrogen specified)	ASTMD4809	MJ/kg	42,974
Sulfur, (XRF)	NM380	mg/kg	5,6

The batches were analyzed by taking the sample straight from the fuel tank. The Fuel batch DFO 031 contained normal acceptable Sulphur content limits and the fuel was normally used for the research.

The lubricating oil was ordinary 10W-40 (Turbo NEX 10W40) engine oil. The used engine oil was supplied by the Neste Corporation. Neste Turbo NEX is effective at sustaining emission control system durability where particulate filters and other advanced aftertreatment systems are used.

2.3 Engine

The research measurements were performed with one prototype Agco Power 49 AWF diesel engine with prototype engine software. The test engine was a turbocharged, intercooled 4-cylinder direct injection engine, used mainly in tractors and combines. The Technical specifications of the engine are given in Table 2.3. No modifications were made to the engine except for the combination of the aftertreatment systems.

Table 2.3. Technical specifications of engine.

Engine manufacturer	**Agco Power**
Type	49 AWF
Cylinder order	In-line, 4 cylinder
Cylinder displacement	4.9 dm3
Cylinder bore	108 mm
Stroke	134 mm
Injection system	Common rail injection system
Rated Power	147 kW / 2100 rpm
Maximum Torque	780 Nm / 1500 rpm

The engine was also equipped with cooled external EGR systems and the amounts of EGR were controlled by an actuator which operates the EGR valve according to the engine speed and load (stepless control).

Picture 2.1 presents the research engine and instrumentation of Table 2.1 installed on it.

Picture 2.1. Engine and instrumentation system on the research engine.

Engine condition targets are presented in Table 2.4. They were set only in Mode 1 (2100 rpm with 100 % loading) and same adjustments were kept during the whole C1-cycle and other load points.

Table 2.4. Targets for Engine Agco Power 49 AWF in Mode 1.

Intake air depressure	35 mbar
Charge air cooler backpressure	100-150 mbar
Exhaust backpressure	depending on AT
Temperature after charge air cooler	50-55°C

2.4 Used Aftertreatment Systems

The HERE project campaign was performed at the TUAS engine dynamometer with co-operation between TUAS, TUT and FMI. The research engine (49 AWF) operated at steady state driving conditions. The research laboratory was planned so that both engine parameter adjustment and different aftertreatment systems are allowed.

The two aftertreatment systems include the following subsystems:

Set A: DOC + fSCR + SCR88

Set B: DOC + DPF+ SCR89

First, two different aftertreatment systems were examined. The aftertreatment systems proposed by Dinex Ecocat for the measurements consists of a Platinum-Palladium diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF) and a selective catalytic reduction unit (SCR) or SCR coated DPF (fDPF) and a small additional SCR unit. A slipcat unit designed for the complete system will be omitted for this study. The two basic system options are presented in Figure 2.1 while the main specifications of those systems are shown in Table 2.5.

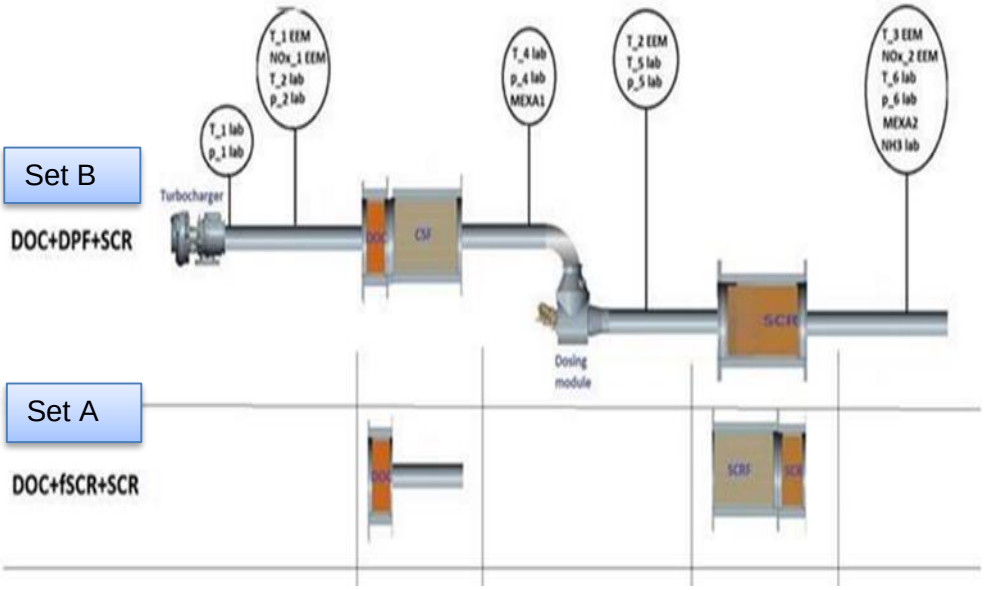
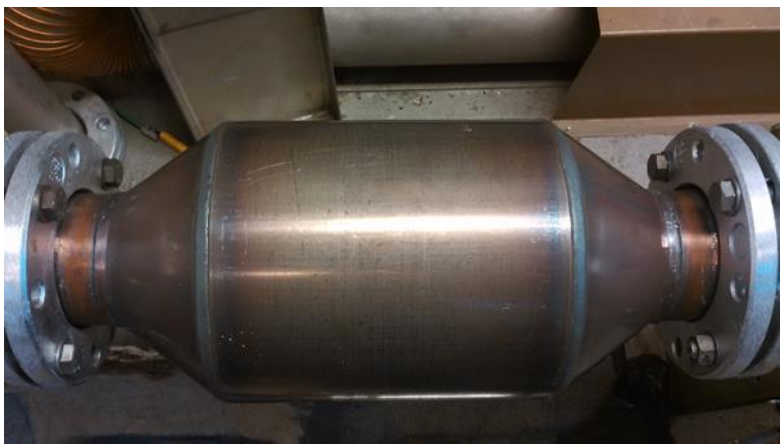


Figure 2.1. Schematic diagram of aftertreatment systems (Dinex Ecocat, mail 12.02.15).

Table 2.5. Main specifications of aftertreatment systems.

	DOC	DPF	SCR88	SCR89	fSCR
Dinex Ecocat					
Serial number	NP12301	NP12387	NP12388	NP12389	NP12386
Volume (l)	3	10.4	4.1	11	10.4
Cells / in^2	200	200	350	350	200
Diameter	159	229	241	241	229
Length	152	254	90	240	254

The fSCR system or SCR on Filter, is a system that comprises SCR coating in DPF cell; specifically, SCR system combines SCR coating which uses urea additive for reaction in particulate filters. Technology of liquid urea dosing systems constantly evolves toward finer spray and use of mixers, allowing shorter mixing length. In parallel, the catalyst industry is continuously improving SCR washcoats which are increasingly more efficient, high-temperature resistant and which can be coated directly on particulate filter substrates (SCRoF for SCR on Filter). These latest developments have opened the door to close-coupled SCR architectures. Picture 2.2 presents the fSCR system utilized in the measurements with insulant inside.



Picture 2.2. fSCR aftertreatment system with insulant inside.

Picture 2.3 presents the SCR aftertreatment system used for the measurements of HERE.

Picture 2.3. SCR aftertreatment system.

APPENDIX 1 presents the piping and instrumentation (PI) diagram of the aftertreatment system test bench in the HERE project. Depending on the aftertreatment system that was tested, several modifications to the test PI diagram and piping of the test bench were made. For example, in tests of aftertreatment set A, the DOC sub-system contains only a DOC aftertreatment system, but in set B DOC and DPF are placed conjointly. In set A the SCR subsystem has only an SCR unit, but set B has an fSCR and an SCR unit.

2.5 Test Procedure

2.5.1 ISO 8178-C1

The following section provides a short description of the experimental program consisting mostly of several different test runs. The emissions were determined according to the emission test cycle of ISO -8178 C1. ISO 8178 is an international standard for exhaust emission measurements designed for off-road engine applications. This standard is utilized in many countries in order to certify engine emissions or for type approval. ISO 8178 is applied for emission measurement and certification in the European Union, United States and Japan. The engine emissions test cycle is defined by reference to the ISO 8178 standard. The ISO 8178 includes a collection of steady-state engine dynamometer test cycles (designated as type C1, C2, D1, etc.) designed for different classes of engines and equipment (Dieselnet, 2015). Every test cycle includes various steady-state modes. ISO 8178 C1 test cycle is referred to as the Non-Road Steady Cycle

(NRSC). For more thorough information on the steady-state modes of C1-cycle, the required references for the whole ISO 8178 – C1 are provided in the Table 2.6. The tests conducted in HERE project refer to Mode 1 and Mode 7 of ISO 8178 – C1 standard test cycles.

Table 2.6. ISO Emission test 8178 C1.

ISO-8178-C1	Engine speed [rpm]	Torque [Nm]	Loading [%]
Mode 1	2100	704	100
Mode 2	2100	528	75
Mode 3	2100	353	50
Mode 4	2100	72	10
Mode 5	1500	817	100
Mode 6	1500	613	75
Mode 7	1500	409	50
Mode 8	995	2	0

2.5.2 Course of Research Phase (Logbook)

2.5.2.1 Preliminary measurements

In preliminary measurements, both systems were prepared with soot accumulation and aging for 2 hours (engine conditions: 2100 rpm, exhaust temperature < 330 °C, alpha ratio = 1) and regeneration with chemistry stabilization for 4 hours (engine conditions: 1500 rpm, load 100 %, alpha ratio = 1).

During the preliminary measurements the alpha ratio was steadily 1 except for the last hour of measurements shown in Set A where it has changed to 0.1 in order to be examined whether the fSCR would regenerate better itself with a very low alpha ratio.

Alpha ratio is the ratio of ammonia molecules (NH_3) to NO_x molecules. The ideal value for alpha ratio is 1:1 based on urea consumption and having NH_3 available for reaction of all of the exhaust NO_x. When NO_x conversion efficiency is low (low temperatures), the alpha ratio is reduced to less than one to avoid NH_3 slip. When NO_x conversion efficiency

is higher, the alpha ratio can be set at values greater than 1. Alpha ratio depends on exhaust temperature and mass flow through the SCR.

Alpha ratio test drives were implemented in preliminary measurements to find out the Urea Slip –limits in order to avoid the slip (the aim is to find where 10-20 ppm NH_3-slip begins so that the maximum dosing is determined – this dosing range can be used in the actual tests). When alpha ratio is equal to 1 all NO_x is converted with set dozing of AdBlue. If alpha ratio is greater than 1 then AdBlue is dozed too much and NO_x is converted but there is a high possibility for NH_3-slip.

The alpha ratio test drives were conducted for the following modes, relative to each aftertreatment set:

- Set A: M1 and M7 Slip = 1.10
- Set B: M1 slip = 1.10 and M7 slip = 1.15

Exhaust temperature is controlled when exceeding low or upper limit ($270^oC < T.exh < 400^oC$). In aging and regeneration phase the following pressure nominal values exist at 2100rpm with 100% loading (147kW):

- Cooler backpressure: 0.1-0.15 bar
- Intake air pressure: 35 mbar
- After cooler temperature: $50 - 55^oC$
- Exhaust pipe backpressure: bp-valve totally open

Measurements taken at 2100 rpm with loading of 153 kW are:

- Cooler backpressure: 0.16 bar
- Intake air pressure: 31, 5 mbar
- After cooler temperature: 52^oC
- Exhaust pipe backpressure: 217mbar

Alpha ratios in the range of 0,9-1,1 where tested for both aftertreatment sets. Alpha ratios chosen for intensive measurement campaign are the following:

- Set A: M1 alpha = 0.9, M7 alpha = 1.05
- Set B: M1 alpha = 0.9, M7 alpha = 1.05

For mode M1 where NO_x conversion efficiency is low, alpha ratio value lower than 1 is selected. On the other hand, for Mode M7 the higher NO_x conversion efficiency allows for alpha ratio values greater than 1.

2.5.2.2 Reference drive

In the reference drive a test start of TUAS devices is implemented without any aftertreatment system. The exhaust gas temperature after the turbine is higher than 350^oC and the temperature after SCR catalyst is higher than 300^oC. The urea dozing minimum temperature is set to 800^oC so that urea is not injected while NO_x and temperature sensors are measuring.

Measurements are taken without aftertreatment systems at 2100 rpm with loading of 156 kW and:

- Cooler backpressure: 110 mbar
- Intake air pressure: 36 mbar
- After cooler temperature: 54^oC

The backpressure controlling valve was totally open all the time, so that it could be seen how the backpressures developed with different ATs.

Maximum oil temperature and maximum after compressor temperatures were set at 140^oC and 200^oC respectively. Engine warming up lasted 20 min and stabilizing for another 7 min.

Measurements were taken without aftertreatment systems at 2100 rpm with loading of 155 kW and:

- Cooler backpressure: 105 mbar
- Intake air pressure: 35 mbar
- After cooler temperature: 52^oC

Engine warming up lasted 44 min and stabilizing for another 7 min.

Measurements were taken without aftertreatment systems at 2100 rpm with loading of 155 kW and:

- Cooler backpressure: 102 mbar
- Intake air pressure: 35 mbar
- After cooler temperature: 53^oC

Engine warming up lasted 50 min and stabilizing for another 10 min.

2.5.2.3 Actual test conditions for Set A

After the reference drive actual tests were implemented, first for aftertreatment set A (DOC+fSCR+SCR88). Measurements were taken at 2100 rpm with 100% loading and:

- Cooler backpressure: 100 mbar
- Intake air pressure: 35 mbar
- After cooler temperature: 53^oC

The backpressure controlling valve was totally open all the time, so that it could be seen how the backpressures developed. Each measurement day the engine warming up lasted about 20 min and stabilizing about 11 min. The whole test was implemented in brake mode. The pressure targets were checked and set only in Mode 1 before every measurement and with the same settings the Mode 7 was driven. The targets were: Cooler backpressure: 100 mbar, Intake air de-pressure: 35 mbar, Temperature after cooler: 55 °C ± 5 °C and Exhaust pipe backpressure: not controlled.

For set A the alpha ratio was set as indicated in the following:

- At 2100 rpm/705 Nm (Mode 1), alpha = 0.9, ac temperature 53^oC and exhaust manifold temperature 662^oC
- At 1500 rpm/409 Nm (Mode 7), alpha = 1.05, ac temperature 24^oC and exhaust manifold temperature 450^oC

After the tests the alpha ratio was set to 0.7 and the engine was left to cool down at 1500 rpm without load until the measurements of both NO_x sensors was the same and exhaust temperature was lower than 150^oC.

Measurements with set A were conducted for Mode 1 and 7 for a total measuring time of 2 h 15 min (Measurement 1). A second measurement was also implemented for Set A in Mode 1 with measuring time of 2 h and in Mode 7 with measuring time of 1 h 30

min. The third measurement of Set A was implemented in Mode 1 with measuring time of 1 h and in Mode 7 with measuring time of 1 h.

After the intensive campaign a slip test drive for Set A was implemented in Mode 7 that lasted 30 min, with alpha ratio = 1.10.

2.5.2.4 Actual test conditions for Set B

After the actual tests of set A, the actual tests for aftertreatment set B (DOC+DPF+SCR89) were implemented. Measurements were taken at 2100 rpm with 100% loading and:

- Cooler backpressure: 100 mbar
- Intake air pressure: 35 mbar
- After cooler temperature: 53^oC

The backpressure controlling valve was totally open all the time, so that it could be seen how the backpressures developed. Each measurement day the engine warming up lasted about 22 min and stabilizing for another 10 min. The whole test was implemented in brake mode. The pressure targets were checked and set only in Mode 1 before every measurement and with the same settings the Mode 7 was driven. The targets were: Cooler backpressure: 100 mbar, Intake air de-pressure: 35 mbar, Temperature after cooler: 55 °C ± 5 °C and Exhaust pipe backpressure: not controlled.

For set B the alpha ratio was set as indicated in the following:

- At 2100 rpm/705 Nm (Mode 1), alpha = 0.9, ac temperature 52^oC and exhaust manifold temperature 670^oC
- At 1500 rpm/409 Nm (Mode 7), alpha = 1.05, ac temperature 23^oC and exhaust manifold temperature 451^oC

After the tests the alpha ratio was set to 0.7 and the engine was left to cool down at 1500 rpm without load until the measurements of both NO_x sensors was the same and exhaust temperature was lower than 150^oC.

Measurements with set B were conducted for Mode 1 and 7 for a total measuring time of 2 h 15 min (Measurement 1). A second measurement was also implemented for set B

in Mode 1 and Mode 7 with measuring time of 1 h 30 min. For set B there was no third measurement.

2.5.2.5 Actual test variables

The actual variables that were measured are presented in the following, common for both aftertreatment sets in Mode 1 (alpha ratio 0.9) and Mode 7 (alpha ratio 1.05):

- NO_x
- NH_3-slip
- NO_x conversion
- Particulate matter and smoke
- NO
- HC
- Fuel consumption
- Pressures
- Slip test for Set A for alpha ratio 1.1

3 RESULTS

3.1 Preliminary

The NO_x conversion efficiency for soot accumulation of aftertreatment system sets A and B were 94% and 89% respectively (Figure 3.1). Conversion efficiency of regeneration in set B was measured at 92% during the period of 4 hours but conversion efficiency of regeneration in set A was 92% for 3 hours and then dropped at 50%.

Efficiency dropped down in set A during the regeneration after 3 hours because the alpha ratio was changed from 1 to 0.1, which made the urea dozing to decrease. The alpha ratio was decreased at the last hour of measurements in order to be examined whether the fSCR would regenerate better itself with a very low alpha ratio. The rapid change of Alpha ratio can be seen in NO_x Conversion, NH_3-slip and NO_x after AT.

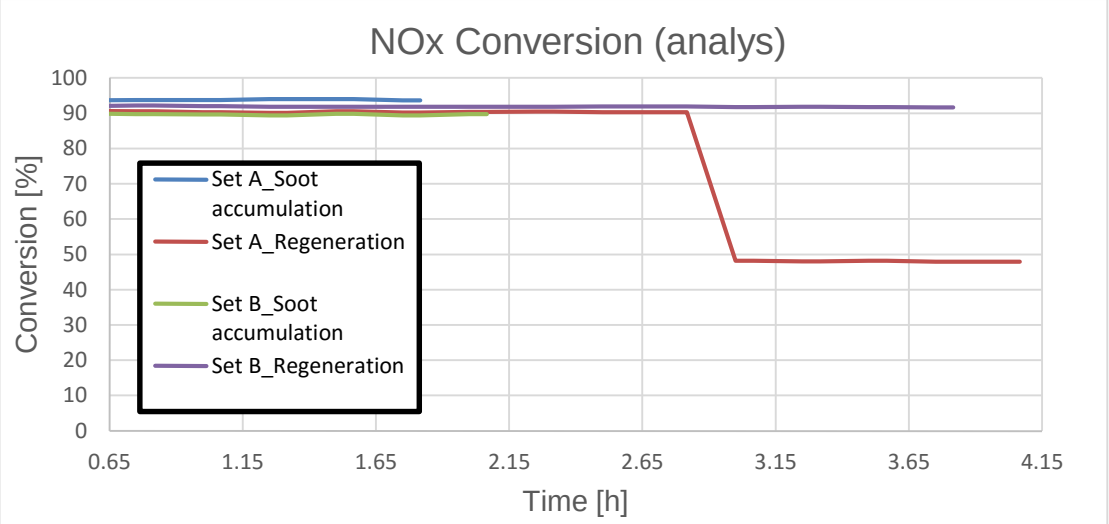


Figure 3.1. NO_x conversion efficiency (preliminary measurements).

Ammonia slip (NH_3-slip) maintains approx. 3 ppm in set A regeneration for 3 hours and then it drops to 0.05 ppm while in the soot accumulation quantity of approx. 0.42 ppm is measured (Figure 3.2). For set B NH_3-slip is around 1 ppm in regeneration and low quantity in soot accumulation approx. 0.05 ppm. The target for NH_3 was less than 10 ppm in every measurement. That is why the regeneration (and also the main measurements) urea slips are in very good range.

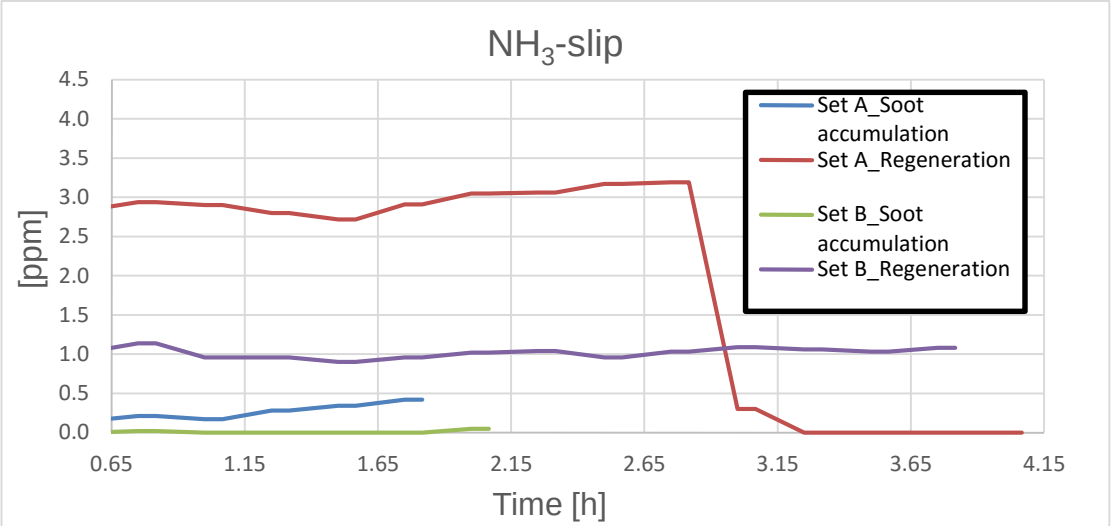


Figure 3.2. Ammonia slip (NH_3-slip) quantity.

Before the AT systems in regeneration mode of both sets, the NO_x emissions were measured at 1050 ppm (Figure 3.3). In soot accumulation mode of both sets before AT, NO_x emissions were at 460 ppm. After the AT system (Figure 3.4), in soot accumulation mode of both sets A and B, NO_x emissions of 40 ppm and 30 ppm were measured. Regeneration NO_x emission were also decreased substantially, namely in set A we measured 100 ppm for 3 hours and for the last hour 530 ppm, while in set B 85 ppm for the whole time range.

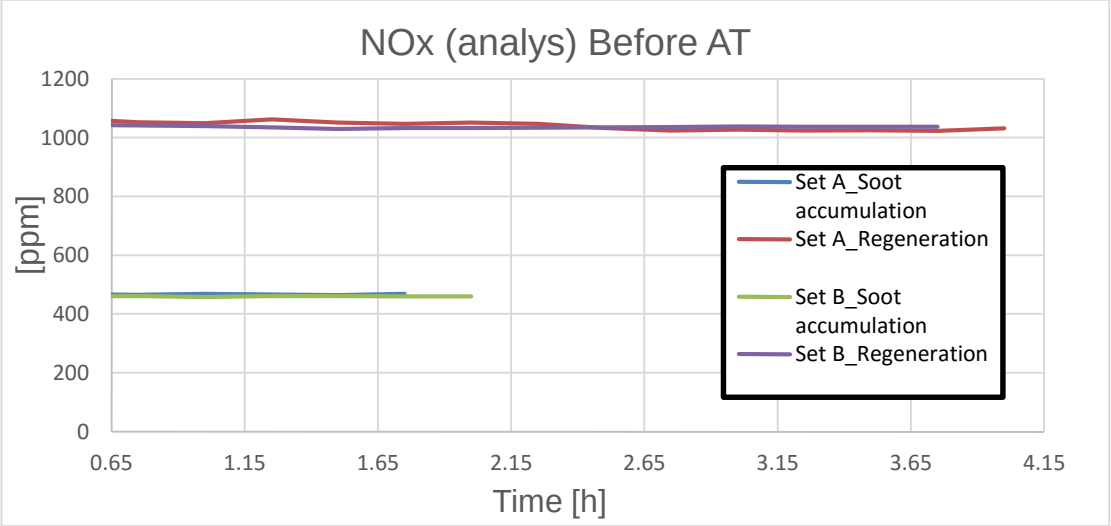


Figure 3.3. NO_x emissions measured before the aftertreatment.

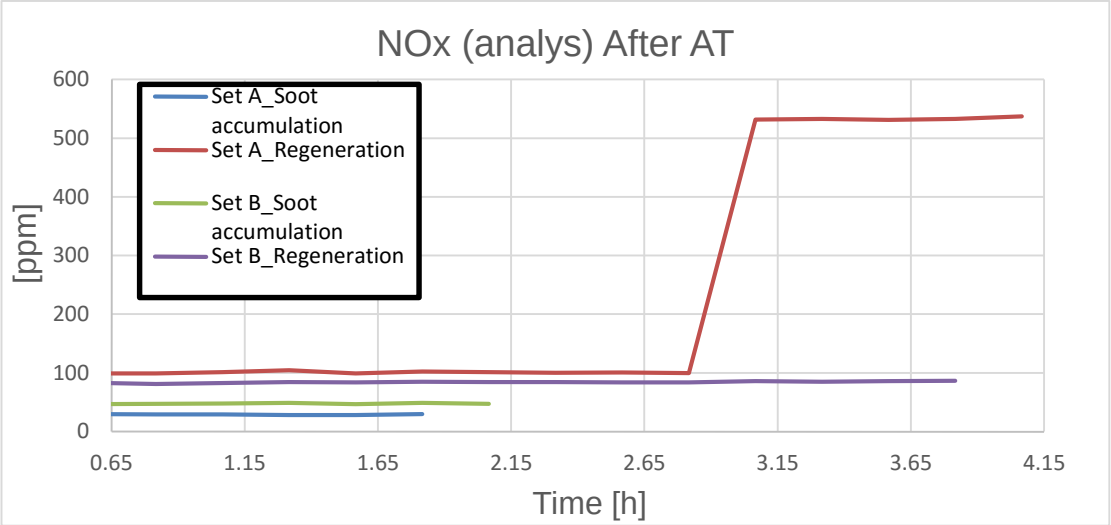


Figure 3.4. NOx emissions measured after the aftertreatment.

The effect of AT systems in particulate matter is shown in Figure 3.5. In soot accumulation mode of set A, PM is very low (approx. 0.024 mg/kWh), while in set B there is a gradual decrease from 2.5 mg/kWh at the beginning of accumulation mode to 0.5 mg/kWh at the end.

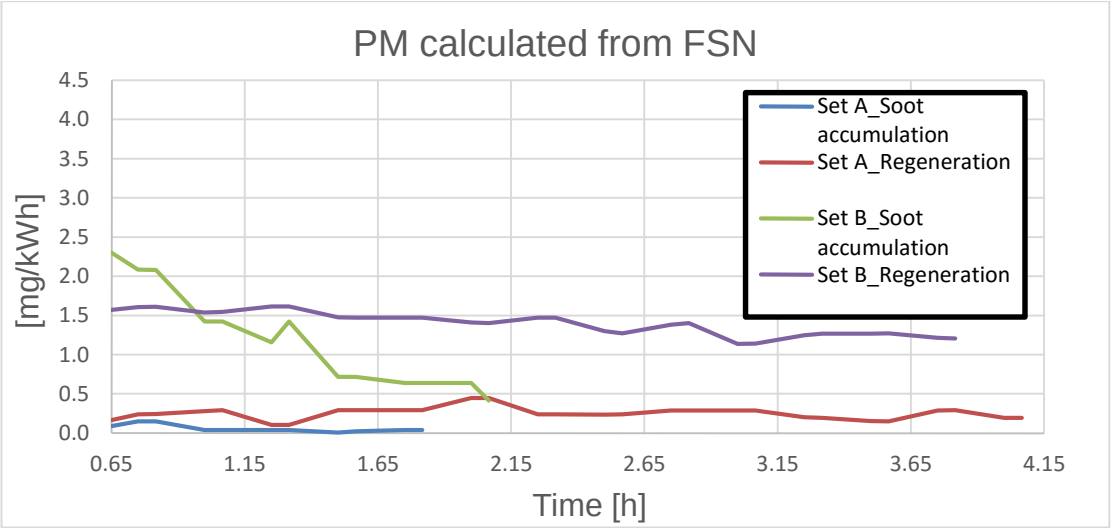


Figure 3.5. Effect of AT systems in particulate matter.

PM of Figure 3.5 were measured in the exhaust smoke after both aftertreatment systems. Smoke presented in Figure 3.6 was measured in FSN (filter smoke number). During soot accumulation set A had approximately null FSN and during regeneration were measured at 0.007 FSN. For set B, smoke was decreasing from 0.028 FSN to 0.007 FSN during the first two hours of the measurement in soot accumulation mode and was between 0.025-0.028 FSN in regeneration mode.

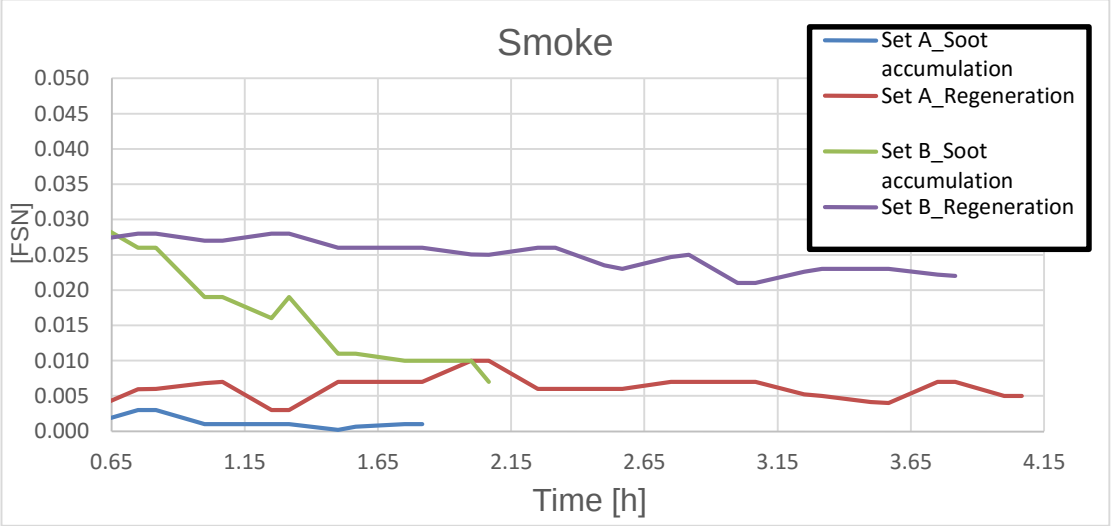


Figure 3.6. Effect of AT systems in smoke.

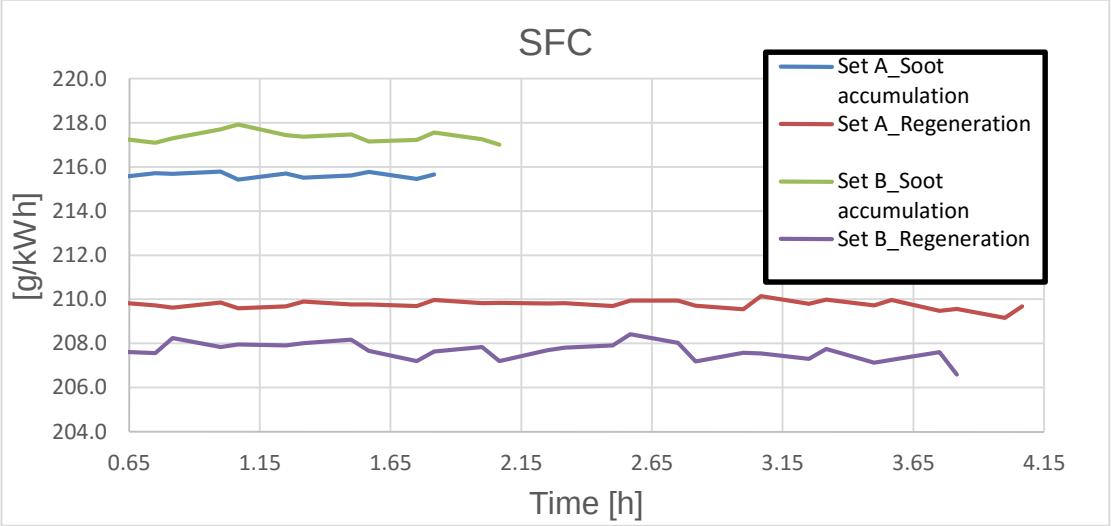


Figure 3.7. Specific fuel consumption after the AT systems.

Specific fuel consumption (SFC) is presented in Figure 3.7. In regeneration SFC is 210 g/kWh and 208 g/kWh for set A and B respectively while in soot accumulation SFC is 216 g/kWh and 218 g/kWh for set A and B respectively.

Fuel flow is presented in Figure 3.8. In soot accumulation, fuel flow is about 5 g/s for both sets, while in regeneration fuel flow is 8 g/s and 7.5 g/s for set A and B respectively.

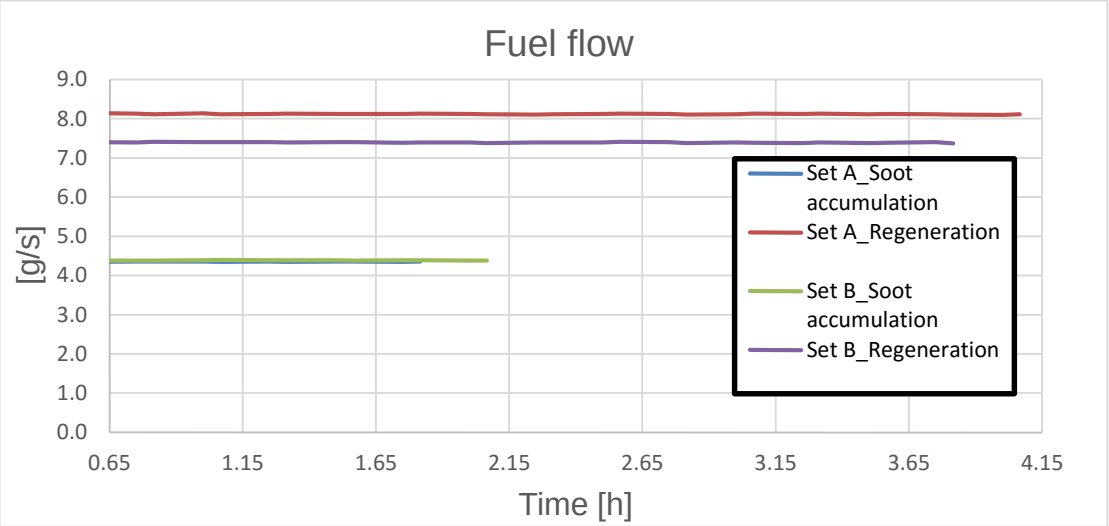


Figure 3.8. Fuel flow after the AT systems.

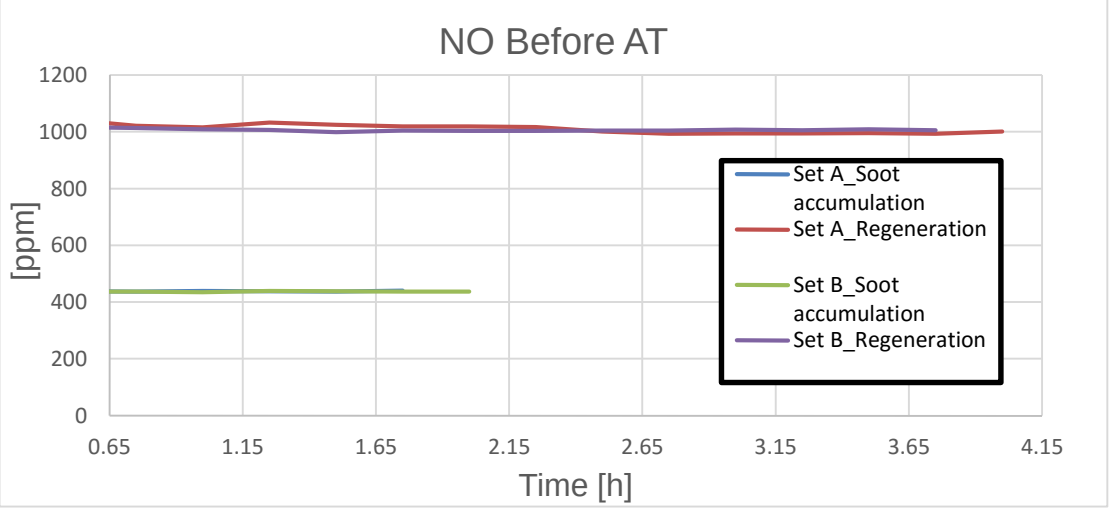


Figure 3.9. Nitrogen monoxide measured before the AT.

Nitrogen monoxide (NO) is measured before and after the AT. Results are presented in Figures 3.9 and 3.10 respectively. Before the AT, NO was measured at 1000 ppm for the regeneration mode and at 450 ppm for the accumulation mode. After the AT, NO was measured at 100 ppm for the regeneration mode and at 10 ppm for the accumulation mode of both sets approximately.

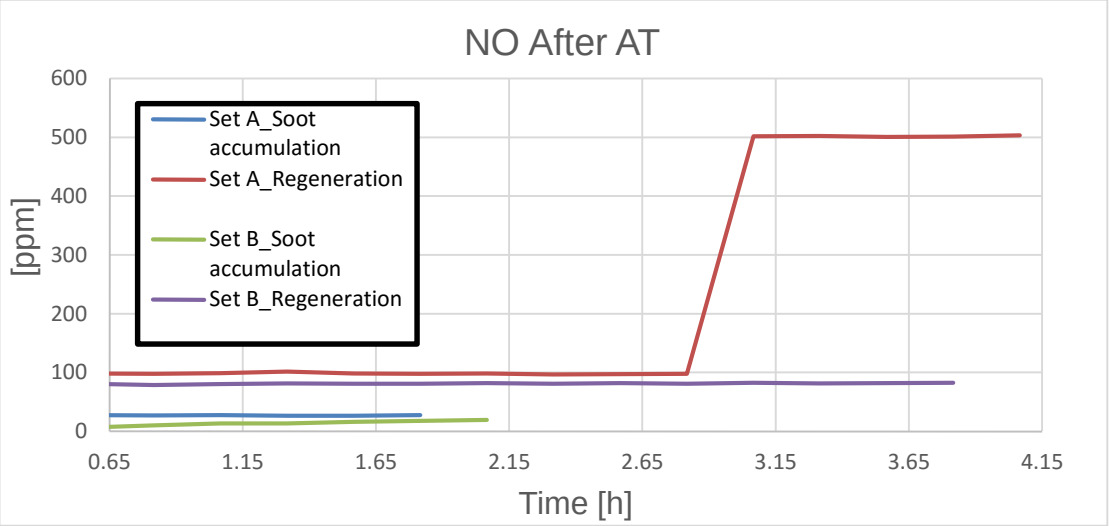


Figure 3.10. Nitrogen monoxide measured after the AT

During soot accumulation HC was measured at approx. 41 ppm before AT and at 10 ppm after AT. During regeneration HC was measured at 20-25 ppm before AT and at 3-4 ppm after AT (Figures 3.11-3.12).

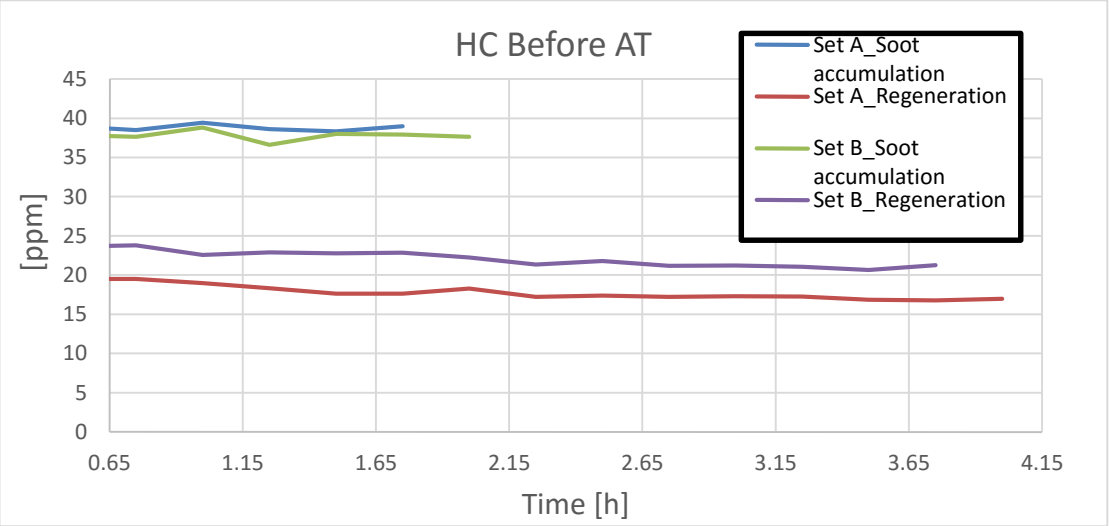


Figure 3.11. Unburnt hydrocarbons before AT.

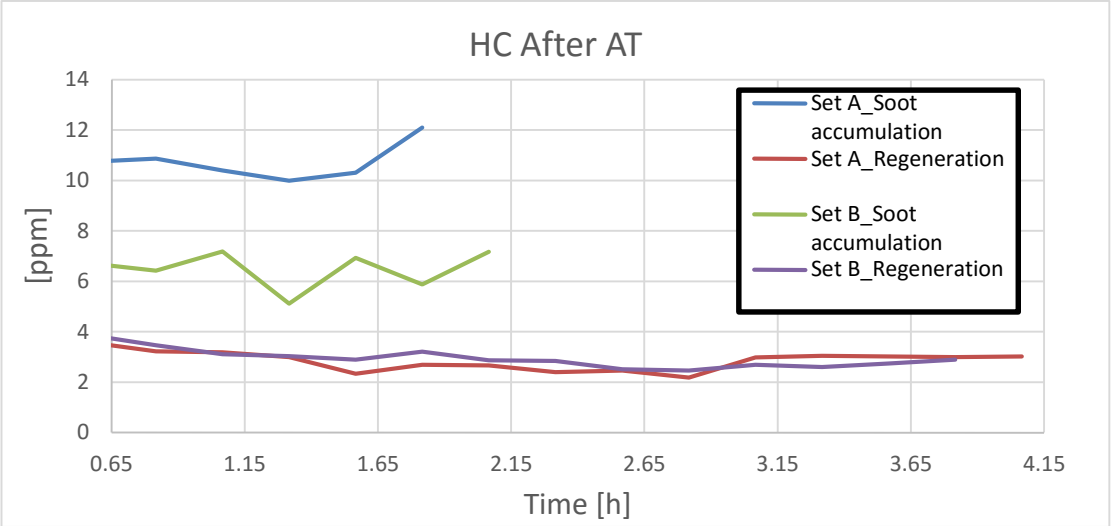


Figure 3.12. Unburnt hydrocarbons after AT.

Exhaust backpressure was measured during regeneration at 180-210 mbar and during soot accumulation at 100 mbar (Figure 3.13). During soot accumulation the pressure over SCR and DOC + DPF remained below 50mbar. During regeneration higher pressures are opposed to SCR and DOC, especially for set A (70 mbar and 30 mbar respectively).

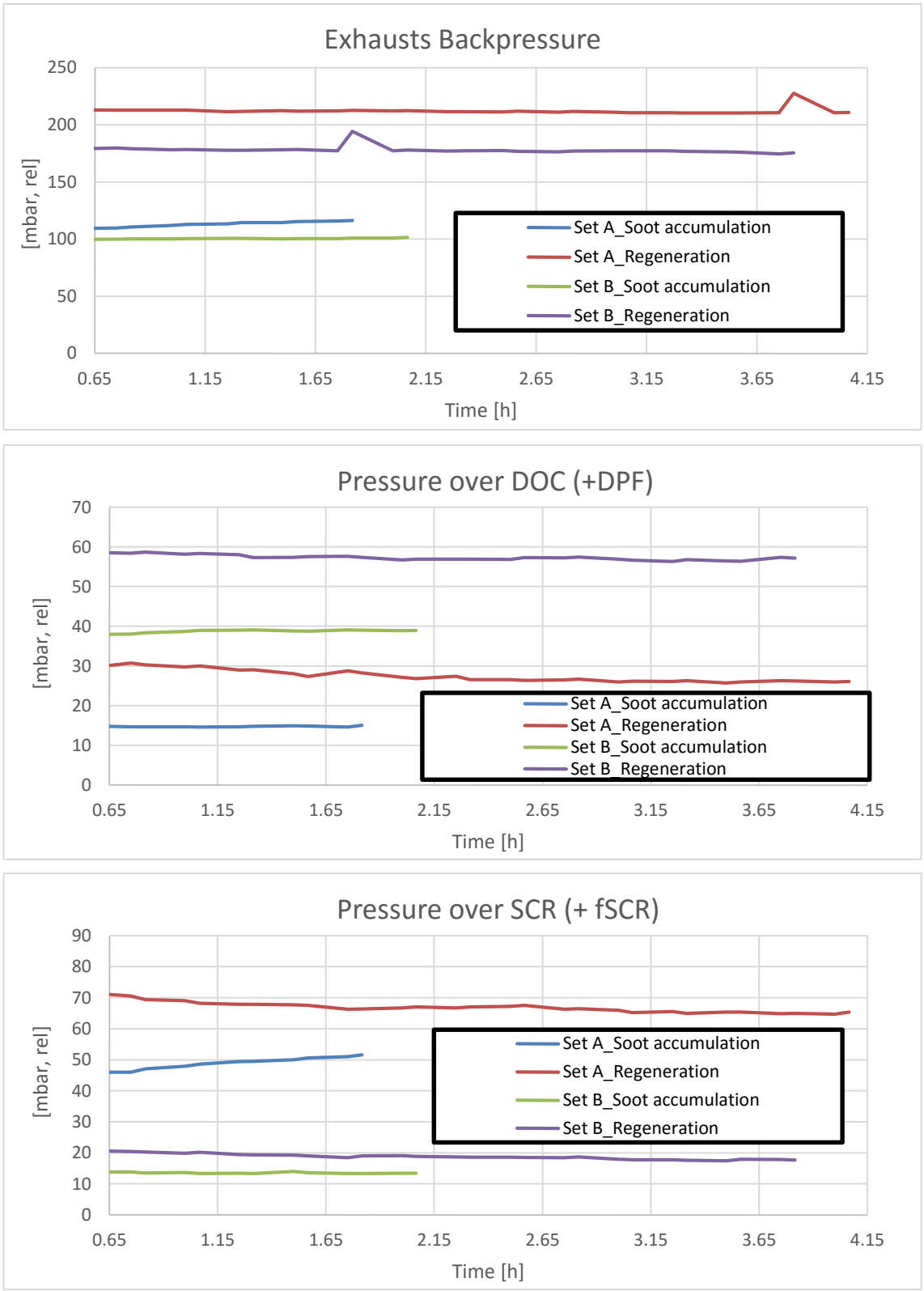


Figure 3.13. Exhaust pressure.

3.2 ISO 8178 C1

The combined emissions of aftertreatment set A are shown in Table 3.1 and the combined emissions of set B are presented in Table 3.2.

Table 3.1. Combined emissions of Set A.

Combined emissions (g/kWh)		
	Before AT	**After AT**
NMHC+NOx	5.16	1.84
NOx	5.07	1.82
NOx sensor	5.39	1.83
HC	0.09	0.02
CO	0.2	0.0
PMFSN (mg/kWh)	0.112	
PMPPS (mg/kWh)	0.165	
SFC	214.7	

Table 3.2. Combined emissions of Set B.

Combined emissions (g/kWh)		
	Before AT	**After AT**
NMHC+NOx	5.28	1.89
NOx	5.19	1.88
NOx sensor	5.53	1.87
HC	0.09	0.01
CO	0.2	0.0
PMFSN (mg/kWh)	1.008	
PMPPS (mg/kWh)	0.766	
SFC	214.1	

The combined emissions before and after the aftertreatment set A are also presented in a graphical form in the figure 3.14. The combined emissions before and after the aftertreatment set B are also presented in graphical form in the figure 3.15. Emission reduction by each emission type for sets A and B is presented in a comparative form in Figure 3.16.

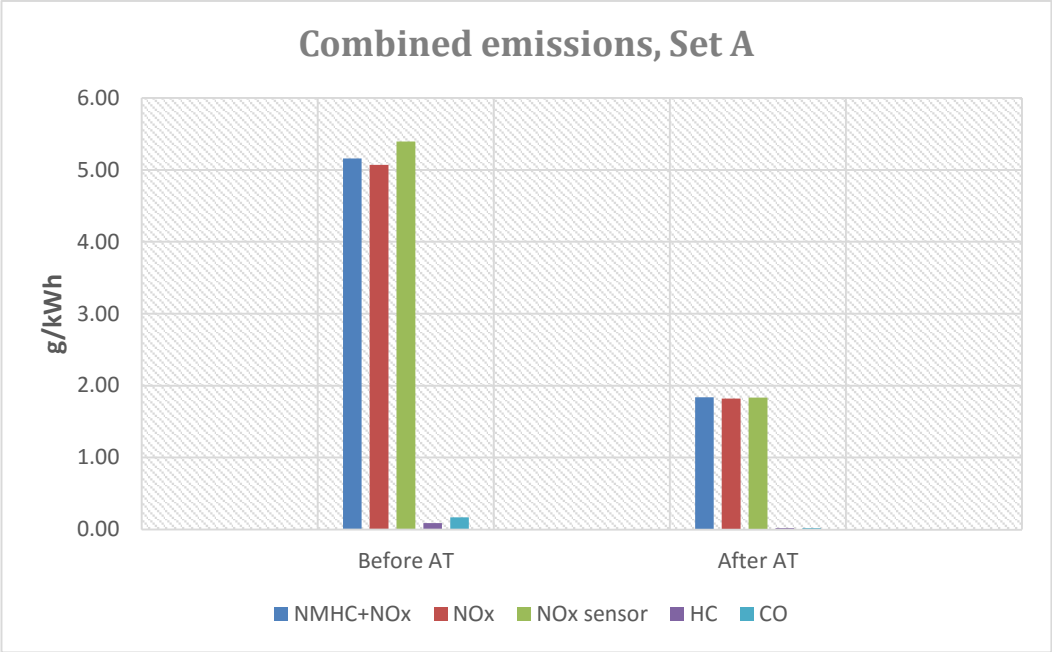


Figure 3.14. Combined emissions before and after set A

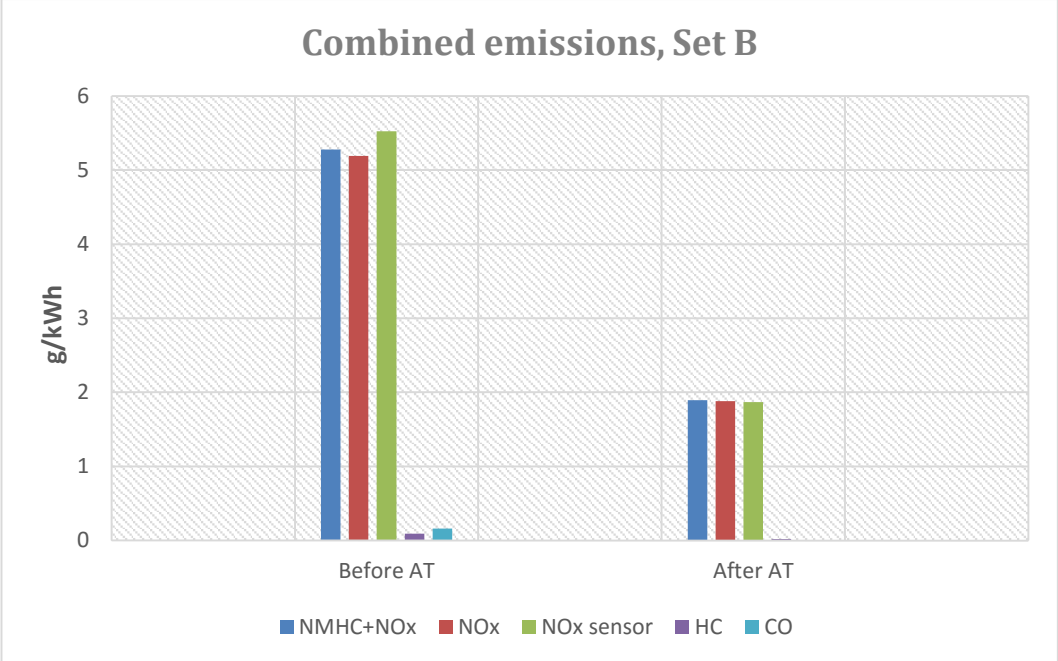


Figure 3.15. Combined emissions before and after set B.

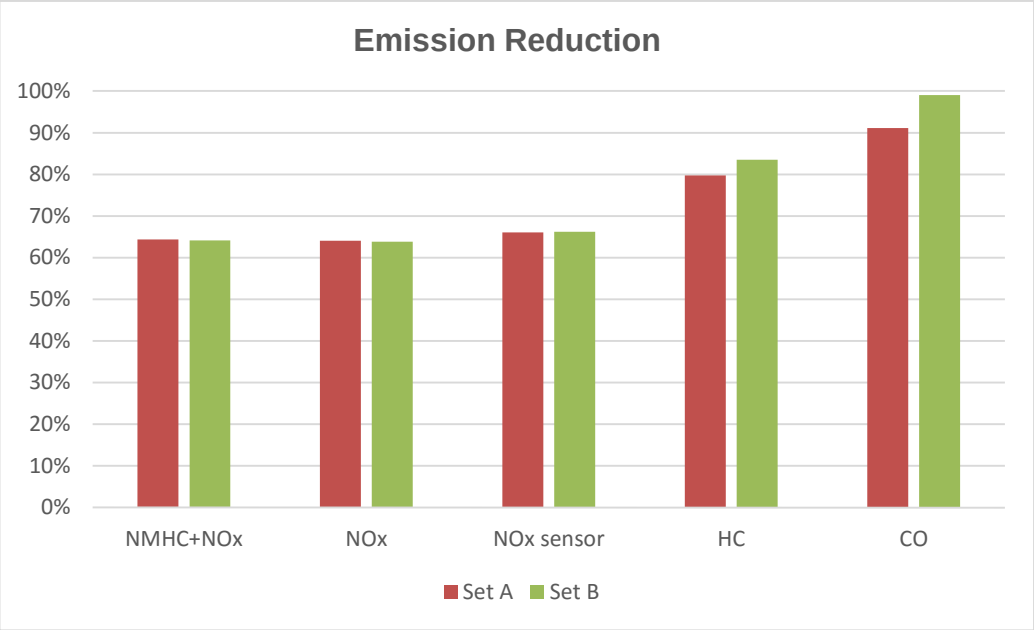


Figure 3.16. Emission reduction by type and aftertreatment set.

3.3 Set A

The NO_x emissions after aftertreatment for set A is presented in Figures 3.17-3.18 for measurements of NO_x analyzer after AT, NO_x sensor TUAS after AT and NO_x sensor EEM after SCR. Figure 3.17 presents data of Mode 1 (engine operating at 2100 rpm and 100% of Torque) and Figure 3.18 presents data of Mode 7 (engine operating at 1500 rpm and 50% of Torque). Measurements are presented for different alpha ratios in the range of 0.75-1.15.

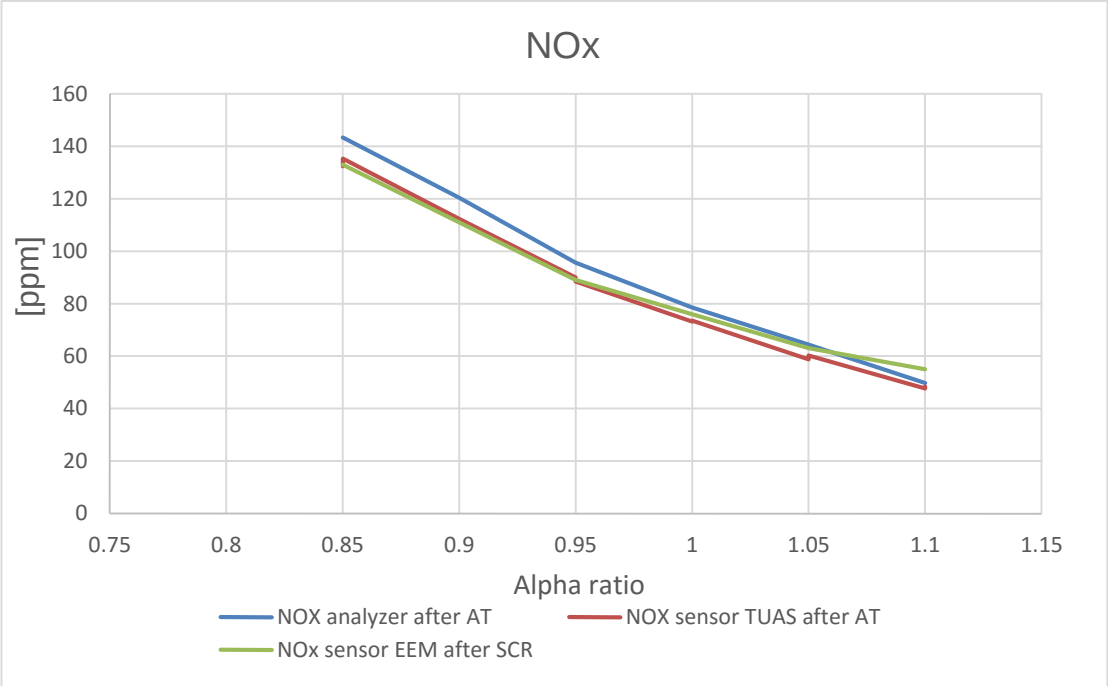


Figure 3.17. NO_x after aftertreatment for set A, mode 1.

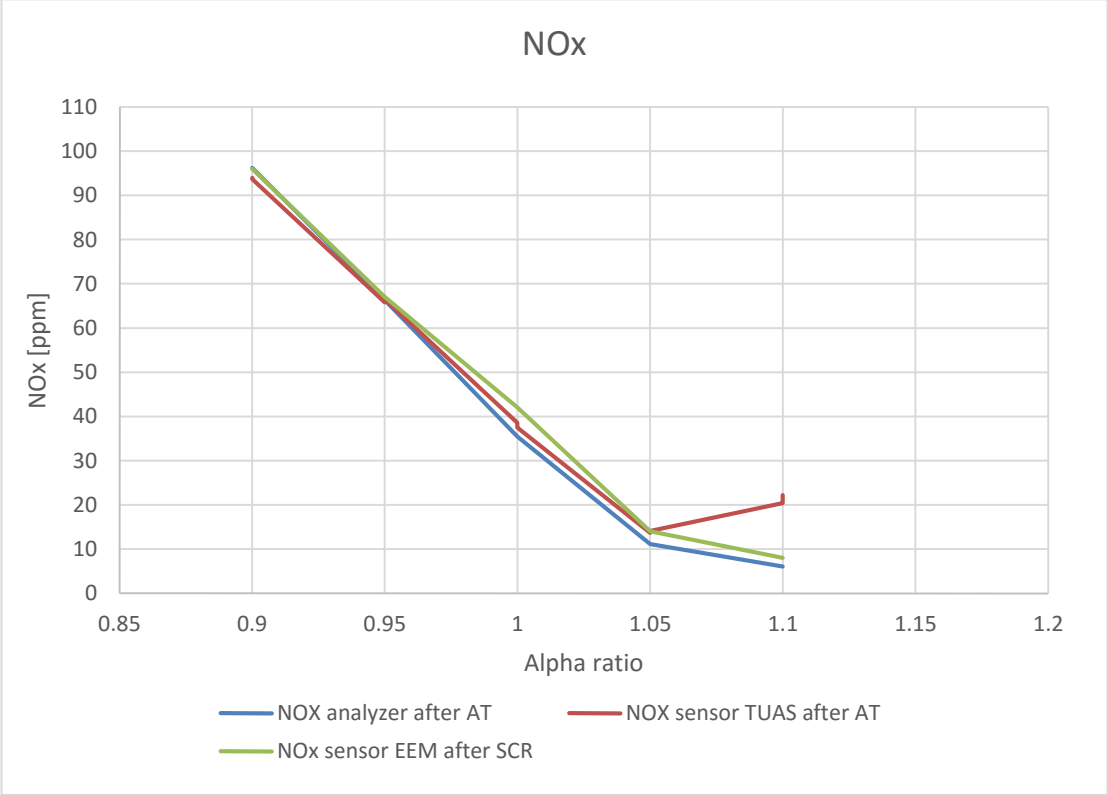


Figure 3.18. NO_x after aftertreatment for set A, mode 7.

The NO_x conversion for set A is presented in Figures 3.19 for the alpha test in Mode 1. As the alpha ratio is increasing NOx conversion is increasing also from 79% to 92%. Measurements are presented for different alpha ratios in the range of 0.85-1.1.

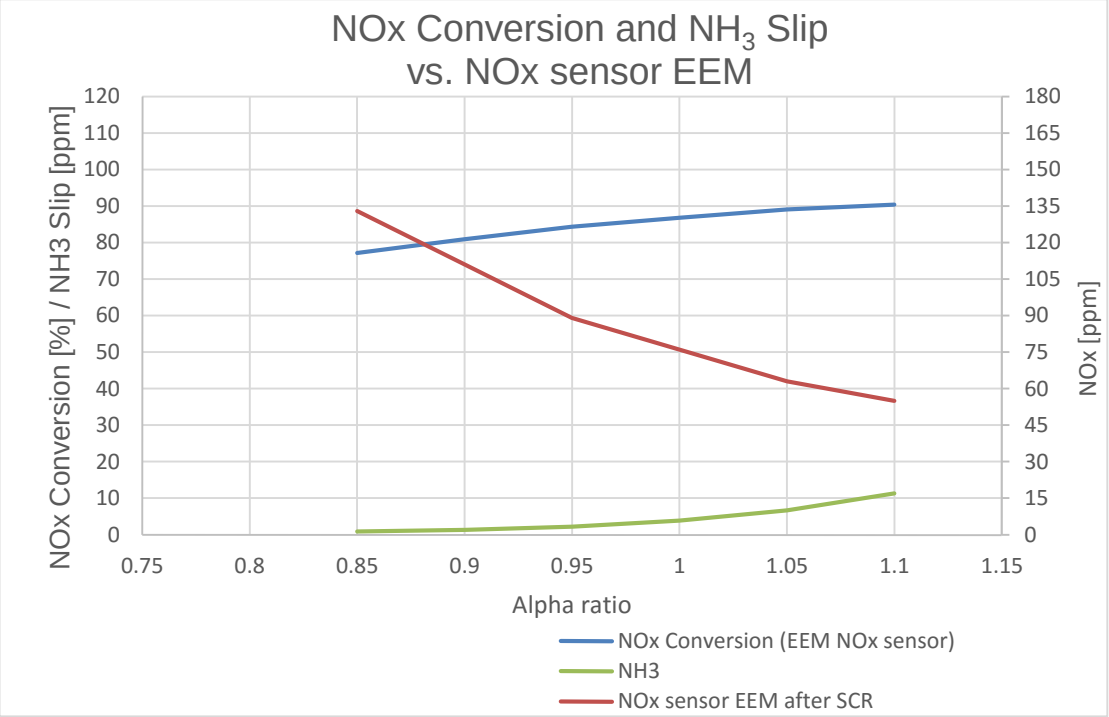


Figure 3.19. NOx conversion for Alpha test in Mode 1.

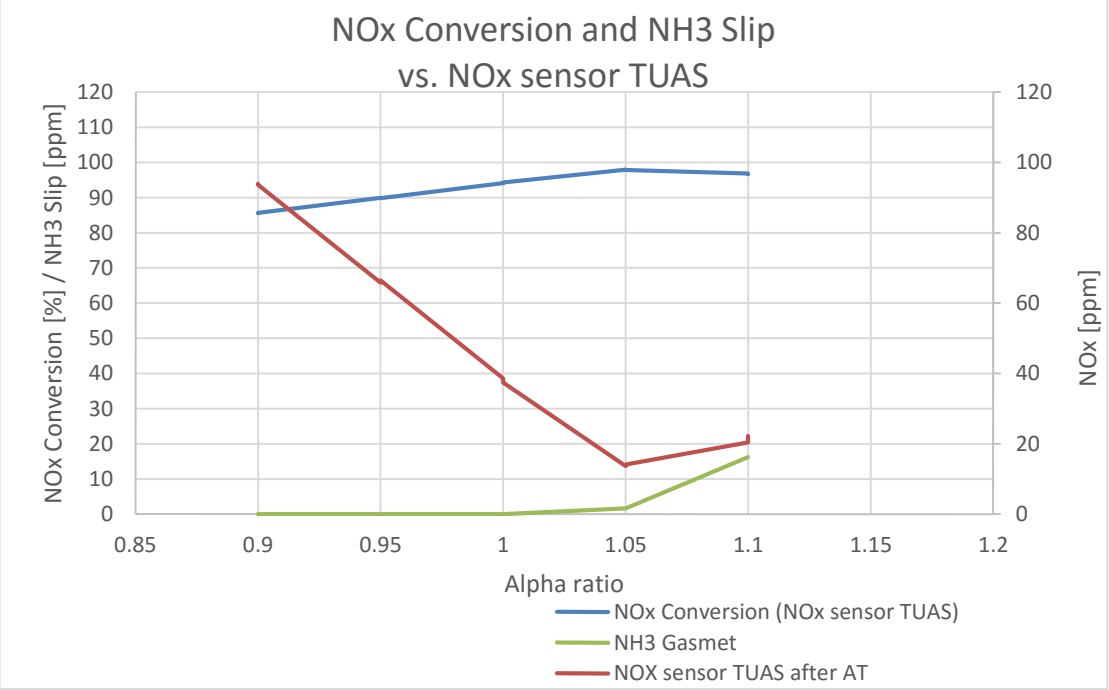


Figure 3.20. NOx conversion for Alpha test in Mode 7.

The NO_x conversion for set A is presented in Figures 3.20 for the alpha test in Mode 7. As the alpha ratio is increasing NO_x conversion is also increasing from 85% to 98%. Measurements are presented for different alpha ratios in the range of 0.9-1.1.

In the following figures, results are presented for the values of the measured variables in the intensive campaign. NO_x conversion in Mode 1 is presented in Figure 3.21. NO_x conversion in the three measurement days is between 78% and 80%. Figure 3.22 presents NO_x conversion for Mode 7 in the range of 94%-98%.

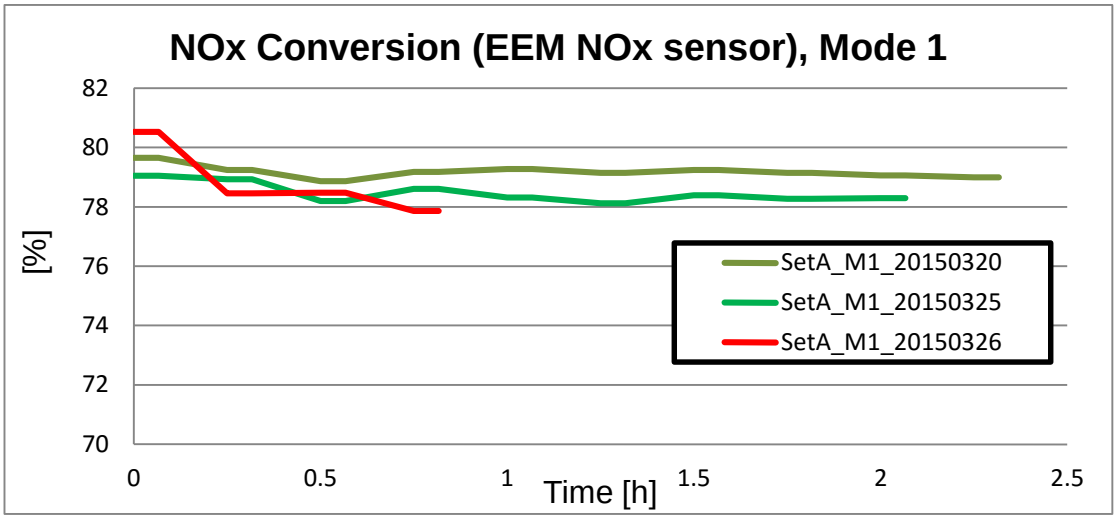


Figure 3.21. NO_x conversion for set A, Mode 1.

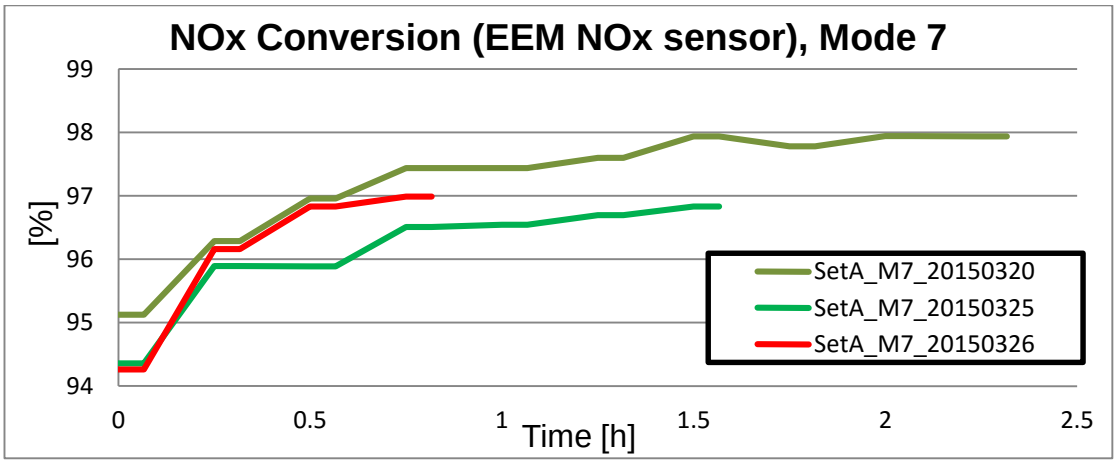


Figure 3.22. NO_x conversion for set A, Mode 7.

NH_3-slip in Mode 1 is presented in Figure 3.23. NH_3-slip in the three measurement days was between 1.6 ppm and 3 ppm. Figure 3.24 presents NH_3-slip for Mode 7 in the range of 0-3 ppm.

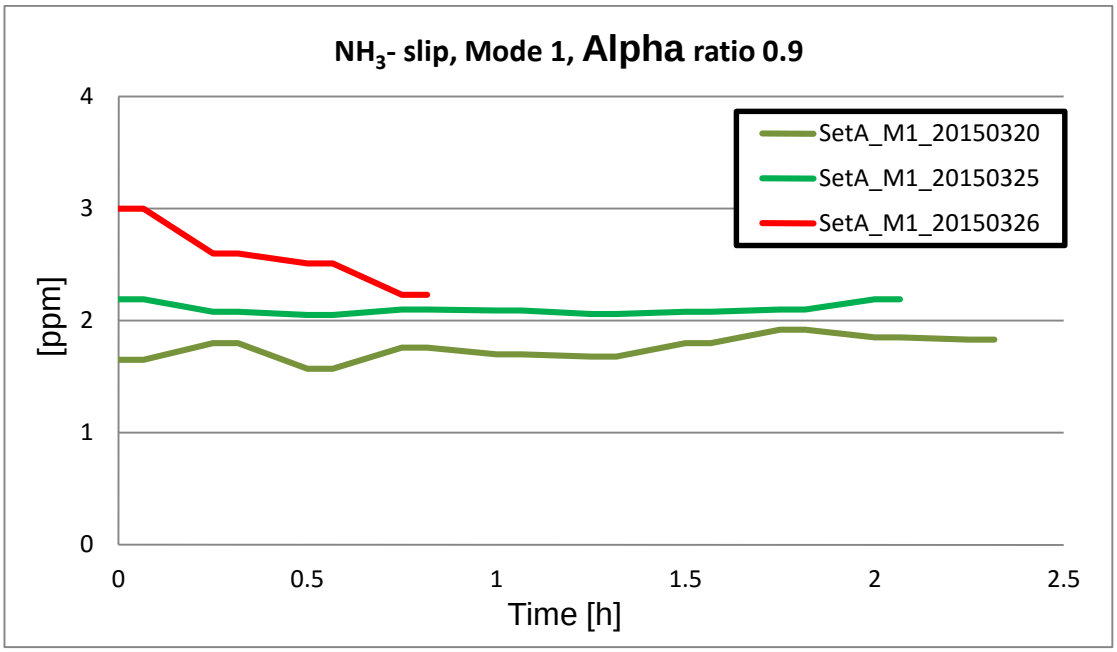


Figure 3.23. NH_3-slip for set A, Mode 1.

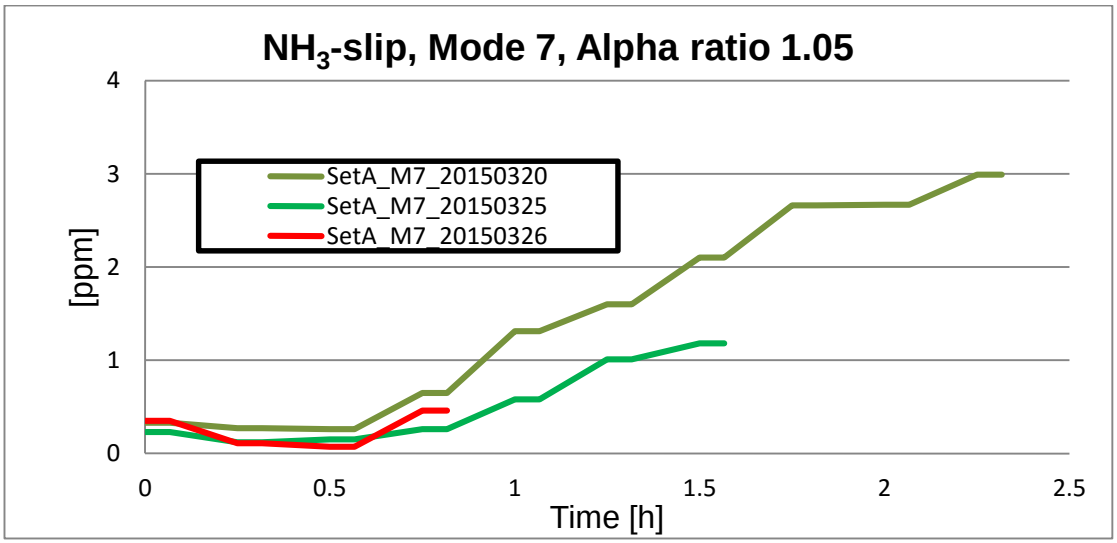


Figure 3.24. NH_3-slip for set A, Mode 7.

NO_x emissions before aftertreatment system in Mode 1 are presented in Figure 3.25. NO_x emissions in the three measurement days were between 665 ppm and 690 ppm. Figure 3.26 presents NO_x emissions for Mode 7 in the range of 670-770 ppm.

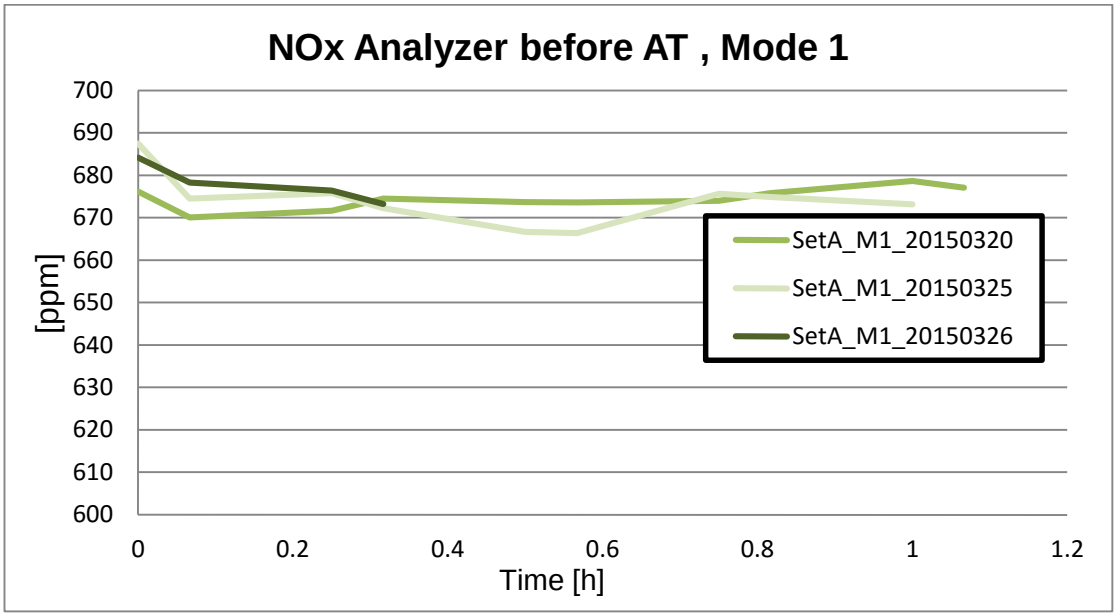


Figure 3.25. NO_x emissions before AT for set A, Mode 1.

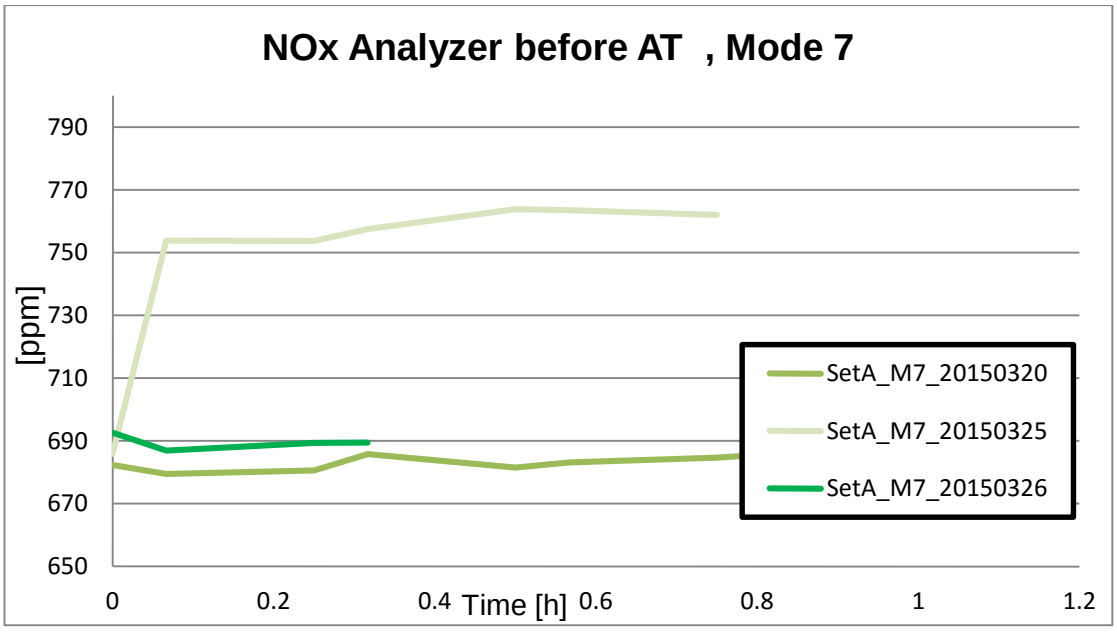


Figure 3.26. NO_x emissions before AT for set A, Mode 7.

NO_x emissions after the aftertreatment system in Mode 1 are presented in Figure 3.27. NO_x emissions in the three measurement days were between 134 ppm and 142 ppm. Figure 3.28 presents NO_x emissions for Mode 7 in the range of 10-30 ppm.

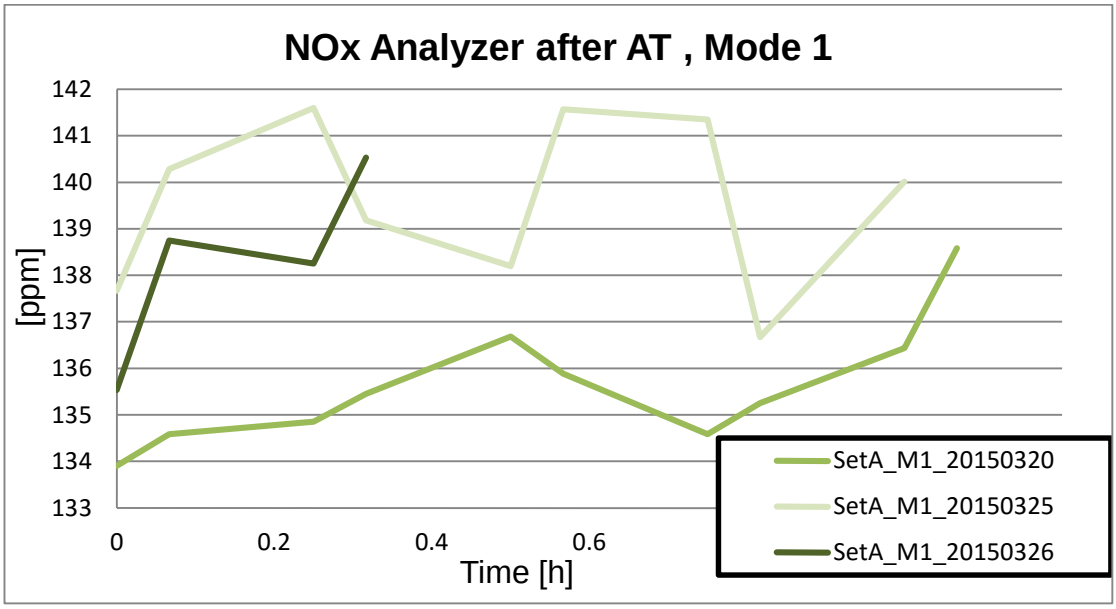


Figure 3.27. NO_x emissions after AT for set A, Mode 1.

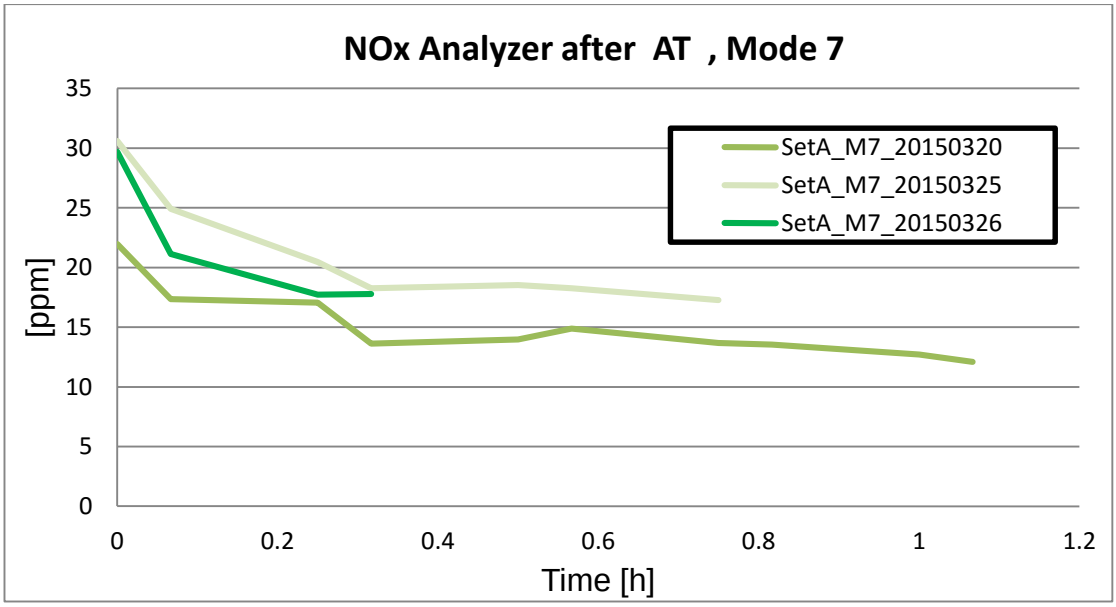


Figure 3.28. NO_x emissions after AT for set A, Mode 7.

PM emissions in Mode 1 are presented in Figure 3.29. PM emissions in the three measurement days were between 0.05 mg/kWh and 0.4 mg/kWh. Figure 3.30 presents PM emissions for Mode 7 in the range of 0-0.18 mg/kWh.

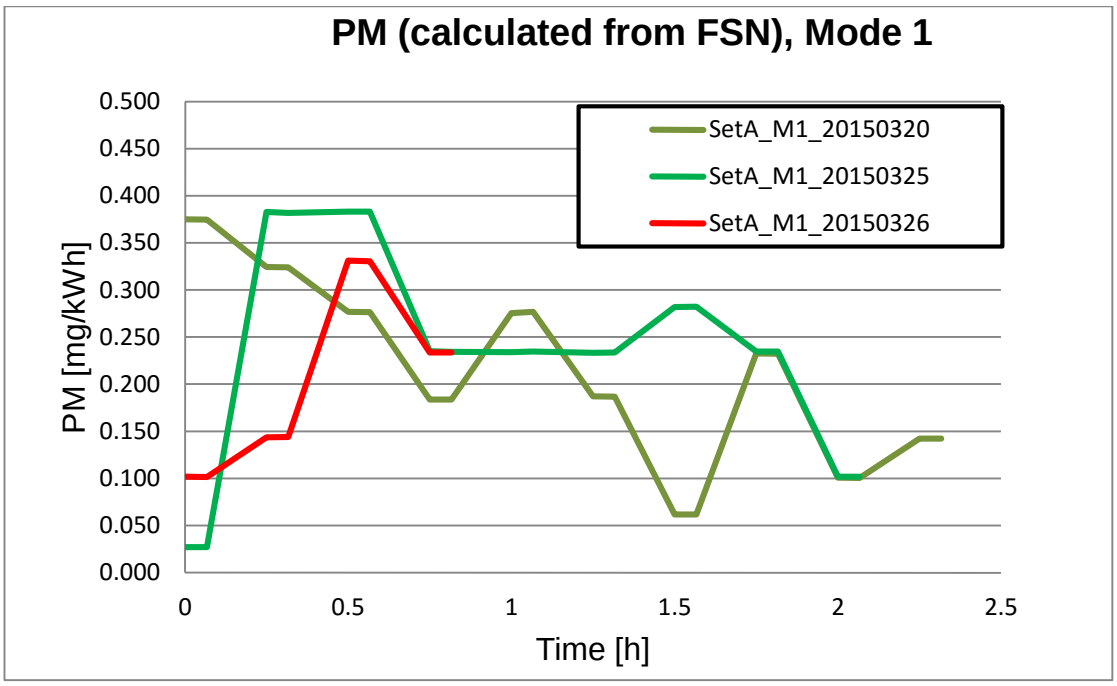


Figure 3.29. PM emissions for set A, Mode 1.

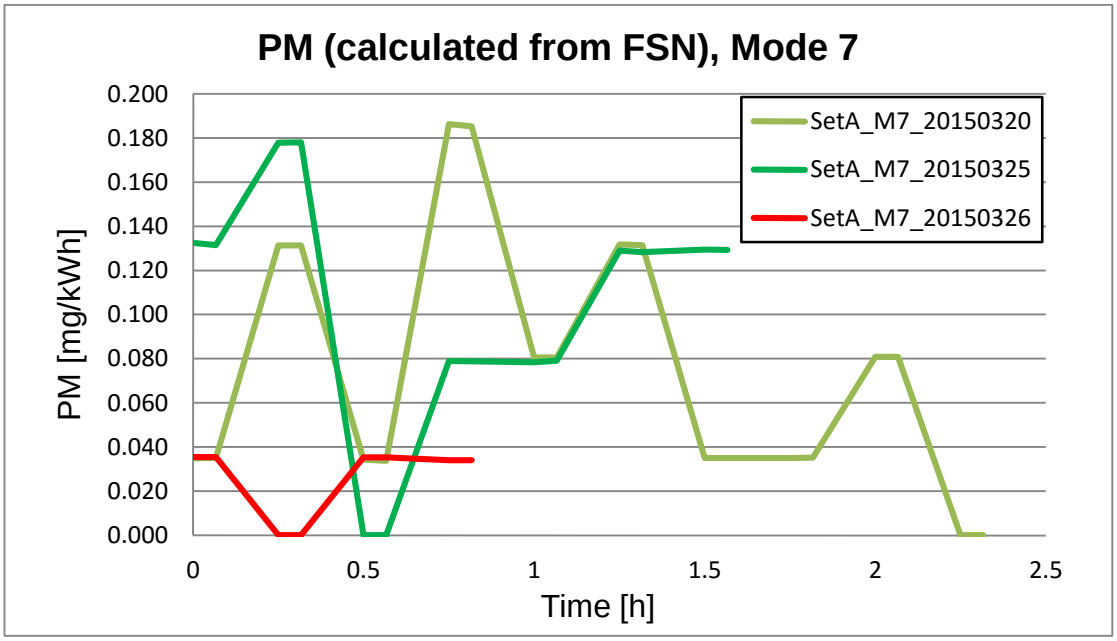


Figure 3.30. PM emissions for set A, Mode 7.

Smoke emissions in Mode 1 are presented in Figure 3.31. Smoke emissions in the three measurement days were between 0 FSN and 0.012 FSN. Figure 3.32 presents PM emissions for Mode 7 in the range of 0-0.04 FSN.

Figure 3.31. Smoke emissions for set A, Mode 1.

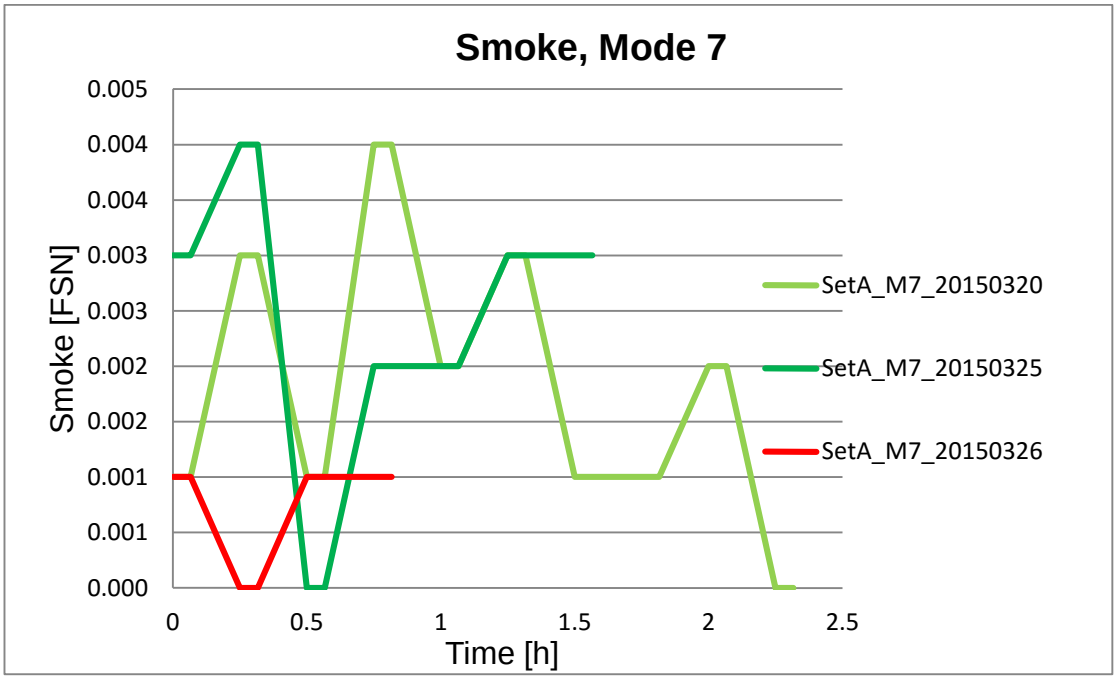


Figure 3.32. Smoke emissions for set A, Mode 7.

Fuel consumption in Mode 1 are presented in Figure 3.33. Fuel consumption in the three measurement days was between 213 g/kWh and 214.5 g/kWh. Figure 3.34 presents fuel consumption for Mode 7 in the range of 201-204.5 g/kWh.

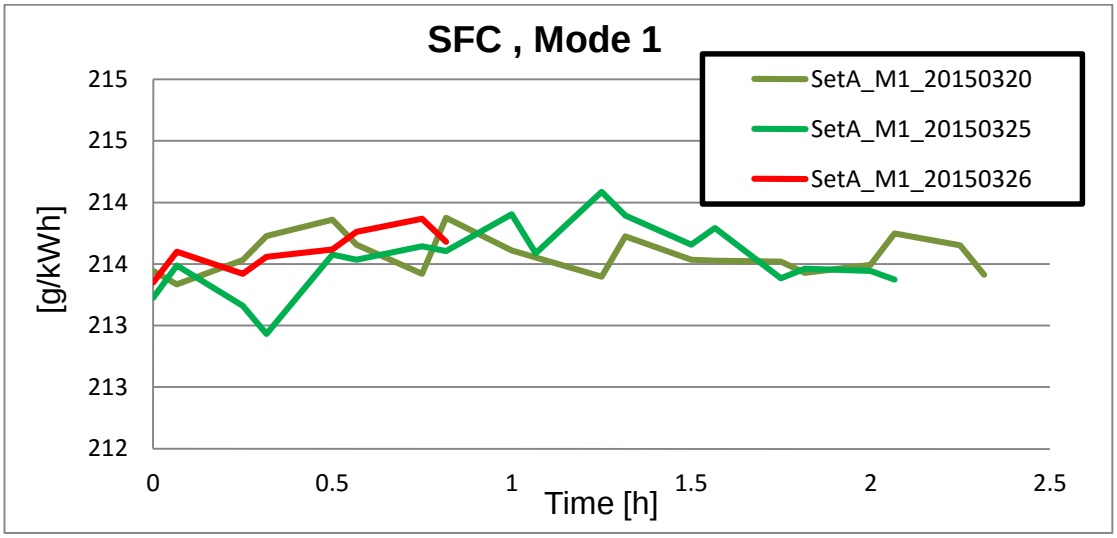


Figure 3.33. Fuel consumption for set A in Mode 1.

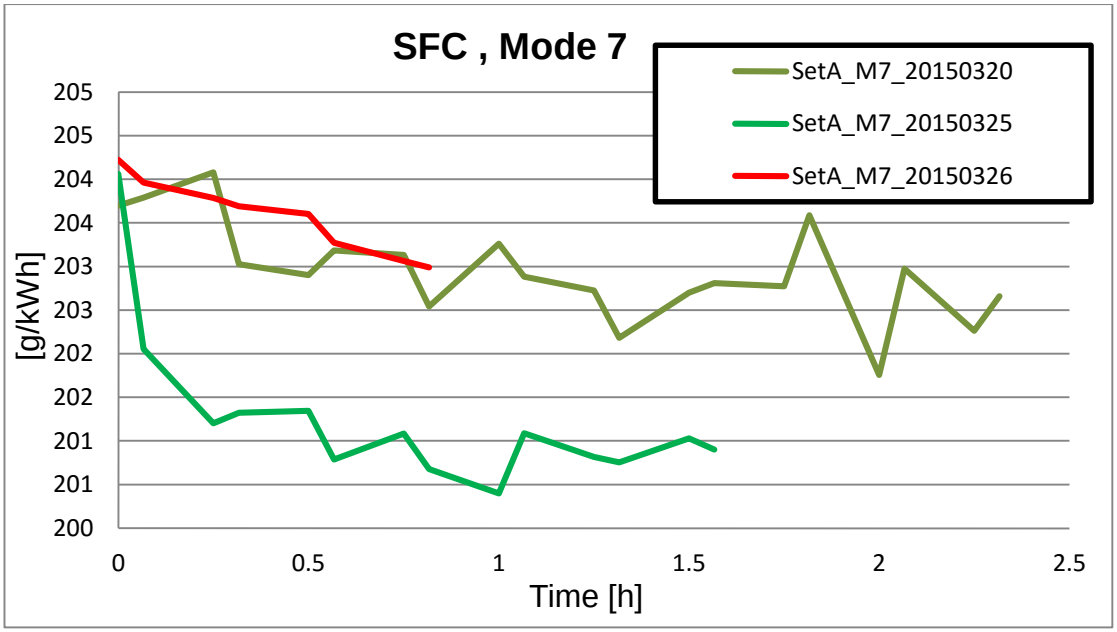


Figure 3.34. Fuel consumption for set A in Mode 7.

Fuel flow in Mode 1 are presented in Figure 3.35. Fuel flow in the three measurement days was between 9.1 g/s and 9.2 g/s. Figure 3.36 presents fuel flow for Mode 7 in the range of 3.6-3.7 g/s.

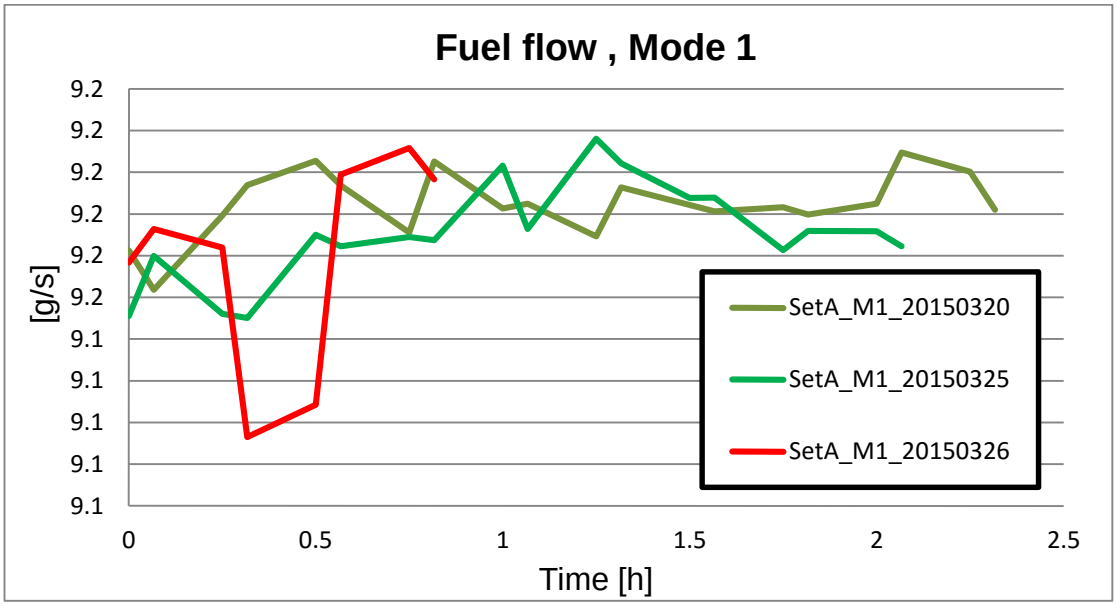


Figure 3.35. Fuel flow for set A in Mode 1.

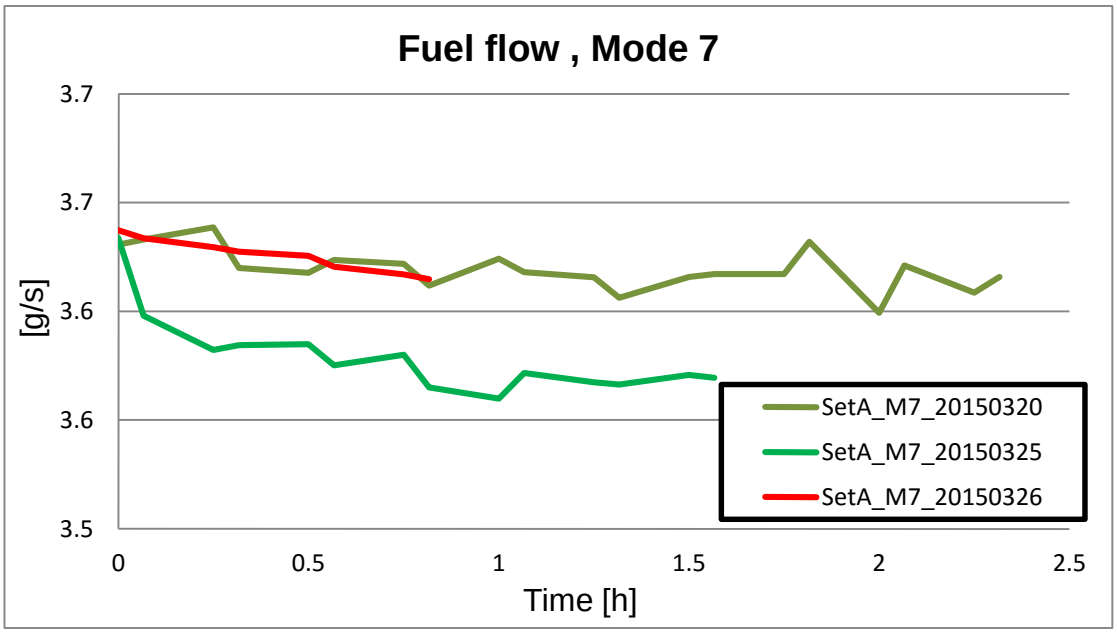


Figure 3.36. Fuel flow for set A in Mode 7.

Exhaust backpressure in Mode 1 is presented in Figure 3.37. Exhaust backpressure in the three measurement days was between 234 mbar and 238 mbar. Figure 3.38 presents fuel flow for Mode 7 in the range of 68-73 mbar.

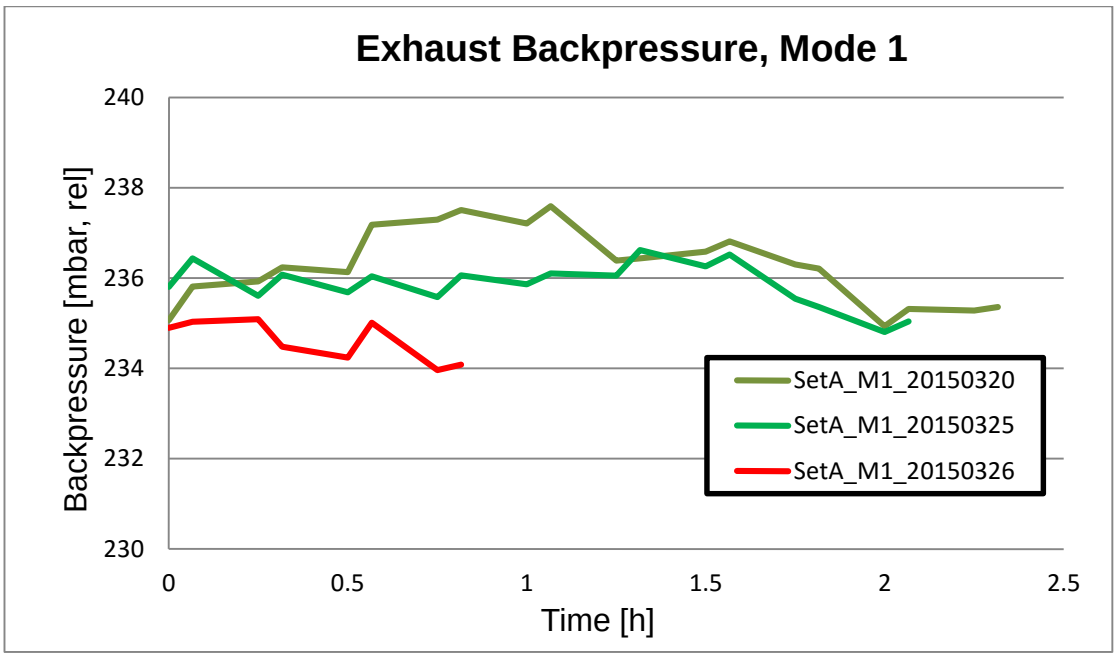


Figure 3.37. Exhaust backpressure, set A in Mode 1.

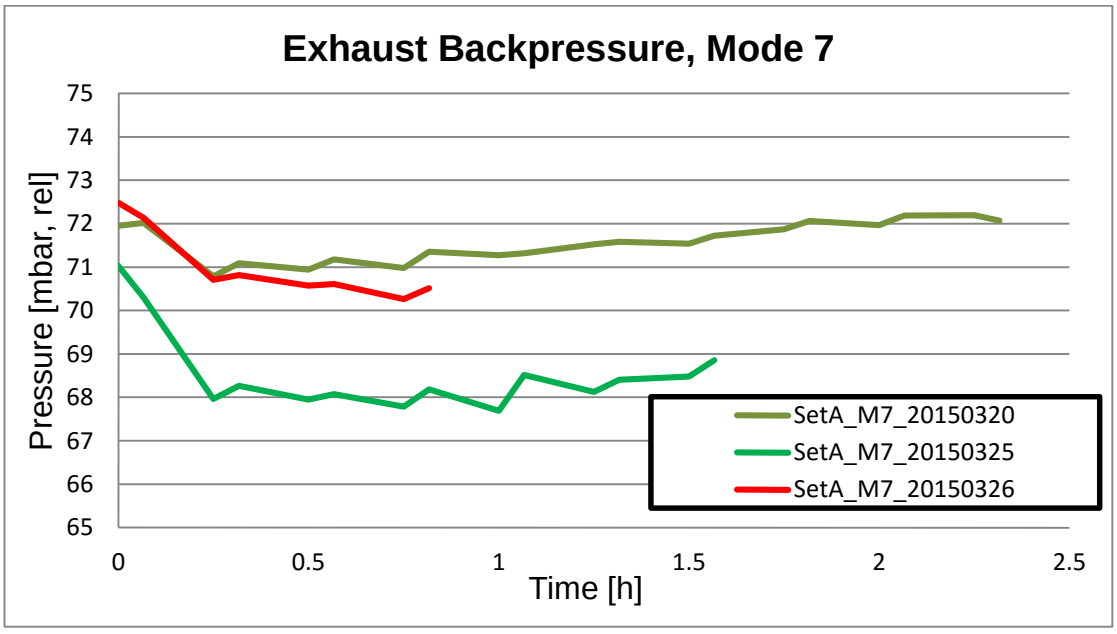


Figure 3.38. Exhaust backpressure, set A in Mode 7.

3.4 Set B

The NOx emissions after aftertreatment for set B is presented in Figures 3.39-3.40 for measurements of NOx analyzer after AT, NOx sensor TUAS after AT and NOx sensor EEM after SCR. Figure 3.40 presents data of Mode 7 (engine operating at 1500 rpm and 50% of Torque) and Figure 3.39 presents data of Mode 1 (engine operating at 2100 rpm and 100% of Torque). Measurements are presented for different alpha ratios in the range of 0.8-1.15.

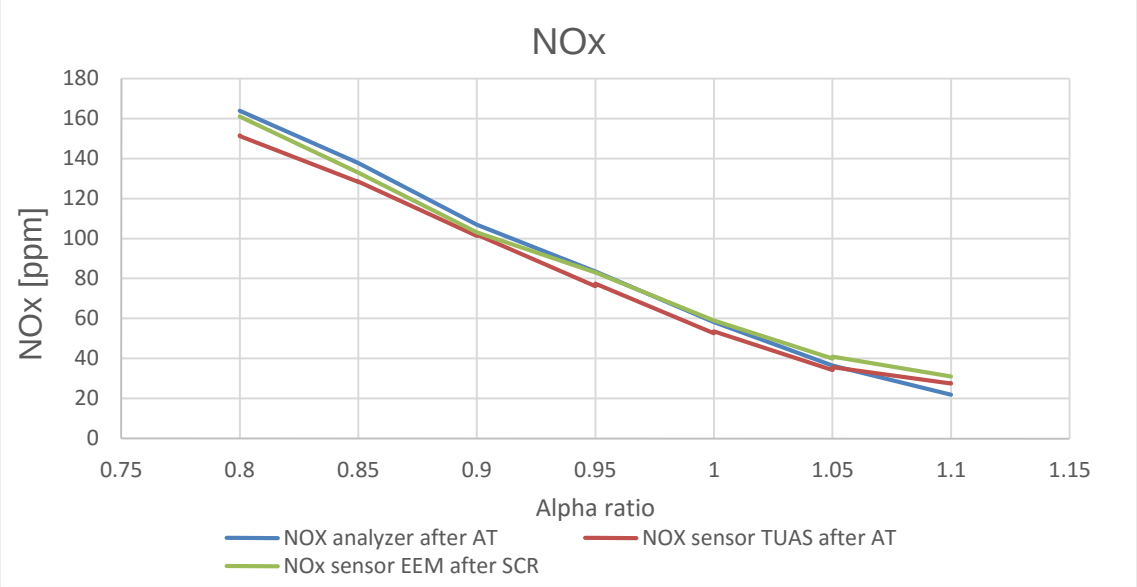


Figure 3.39. NO_x after aftertreatment for set B, mode 1.

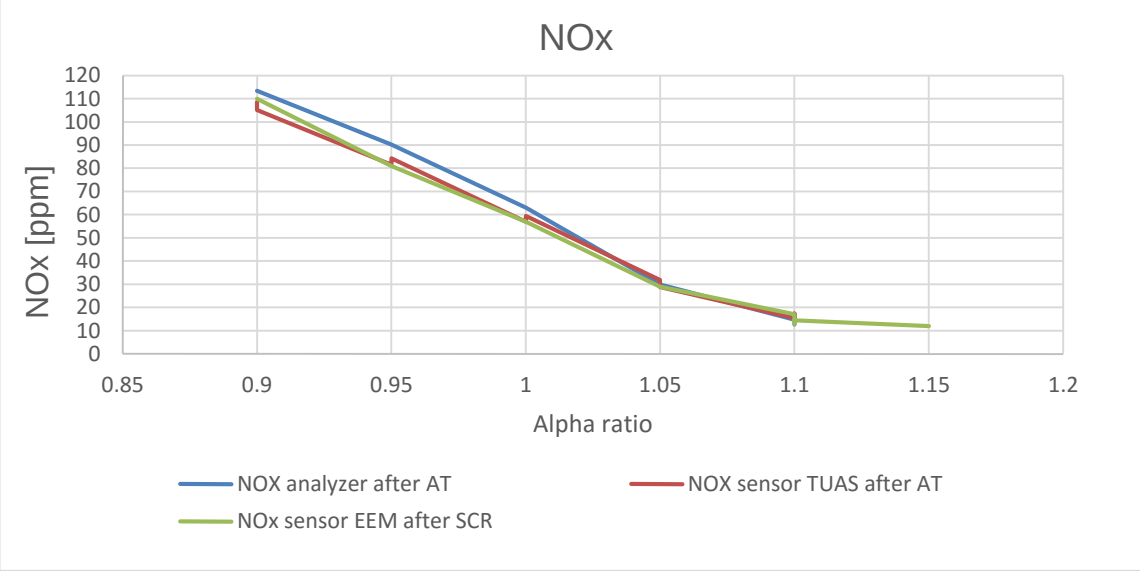


Figure 3.40. NO_x after aftertreatment for set B, mode 7.

NO_x emissions in Mode 1 is greater for set B at alpha ratios lower than 1. Set B presents greater NO_x conversion at alpha ratios greater than 1. NO_x emissions in Mode 7 is greater for set B at alpha ratios lower than 1. Set B presents greater NO_x conversion at alpha ratios greater than 1 for Mode 7.

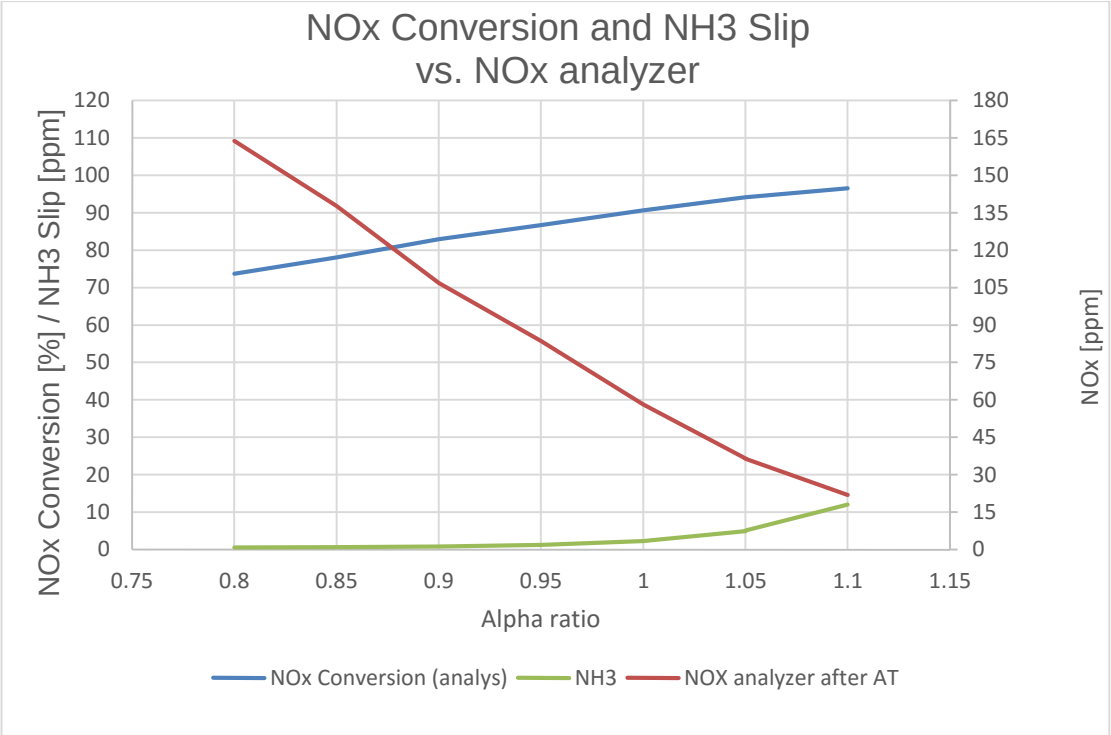


Figure 3.41. NO_x conversion for Alpha test of set B in Mode 1.

The NO_x conversion for set B is presented in Figures 3.41 for the alpha test in Mode 1. As the alpha ratio is increasing NO_x conversion is increasing also from 70% to 100%. Measurements are presented for different alpha ratios in the range of 0.8-1.1.

The NO_x conversion for set B is presented in Figures 3.42 for the alpha test in Mode 7. As the alpha ratio is increasing NO_x conversion is increasing also from 80% to 100%. Measurements are presented for different alpha ratios in the range of 0.9-1.15.

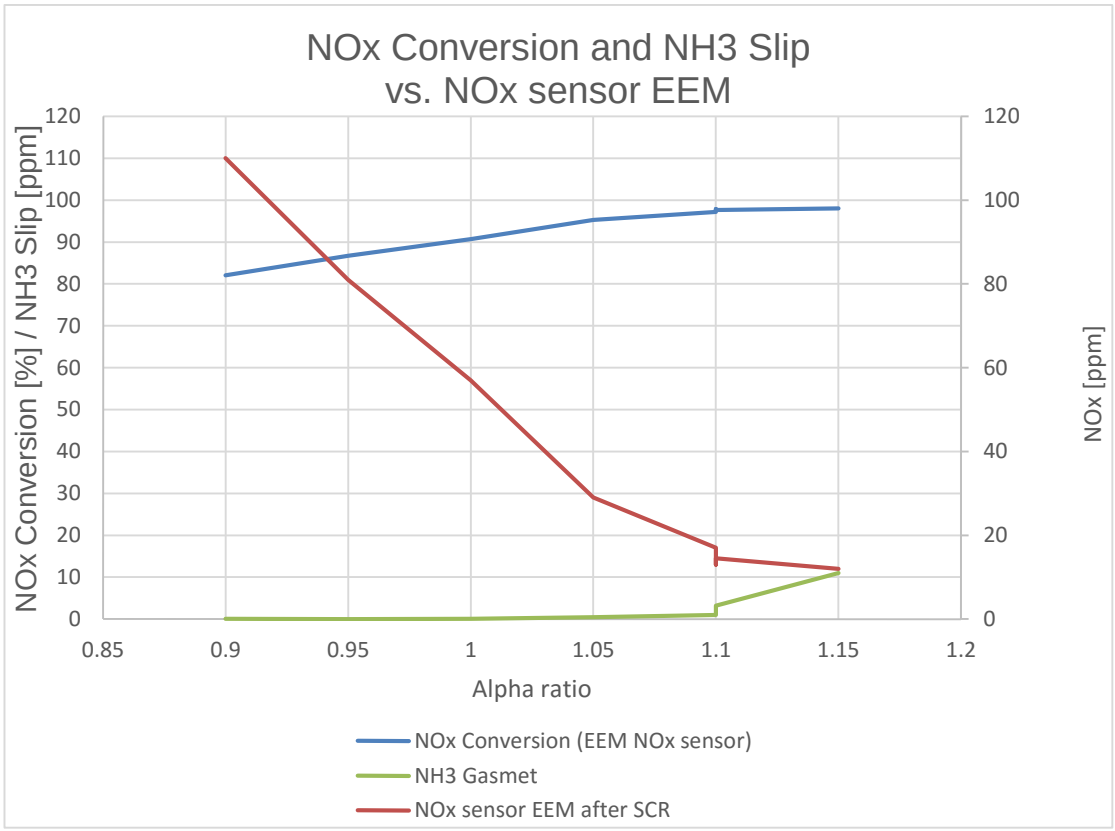


Figure 3.42. NO_x conversion for Alpha test of set B in Mode 7.

In the following figures, results are presented for the values of the measured variables in the intensive campaign of set B. NO_x conversion in Mode 1 is presented in Figure 3.43. NO_x conversion in the two measurement days is between 82.6% and 83.6%. Figure 3.44 presents NO_x conversion for Mode 7 in the range of 88%-94%.

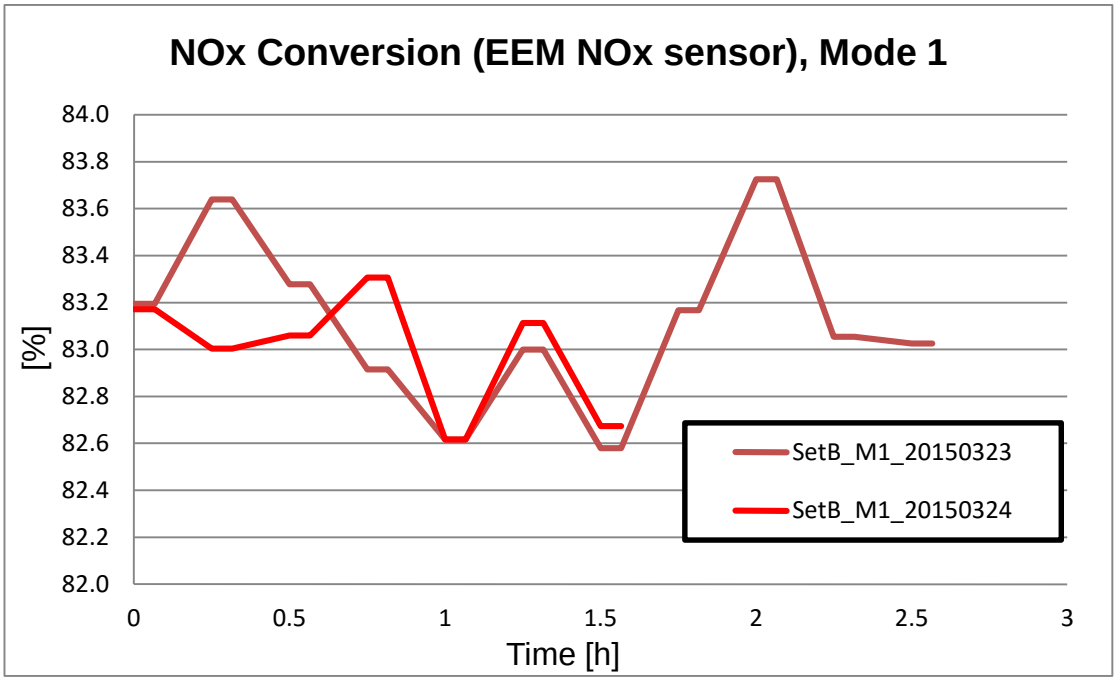


Figure 3.43. NO_x conversion for set B, Mode 1.

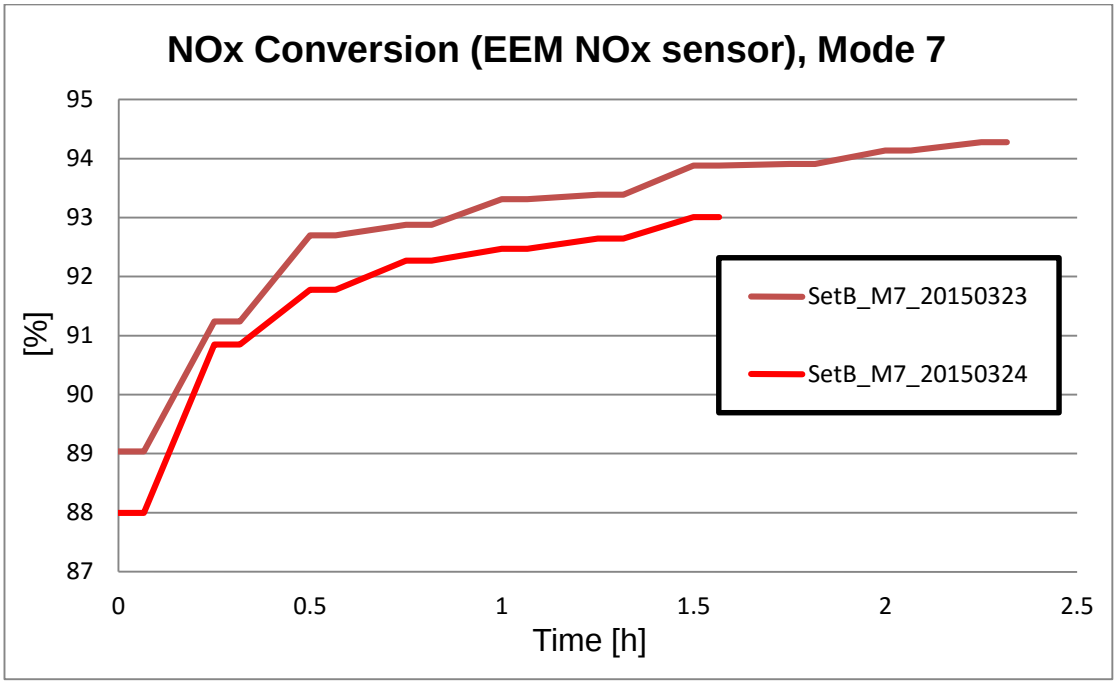


Figure 3.44. NO_x conversion for set B, Mode 7.

NH_3-slip in Mode 1 is presented in Figure 3.45. NH_3-slip in the two measurement days was between 0.5 and 1.2 ppm. Figure 3.46 presents NH_3-slip for Mode 7 in the range of 0-0.9 ppm.

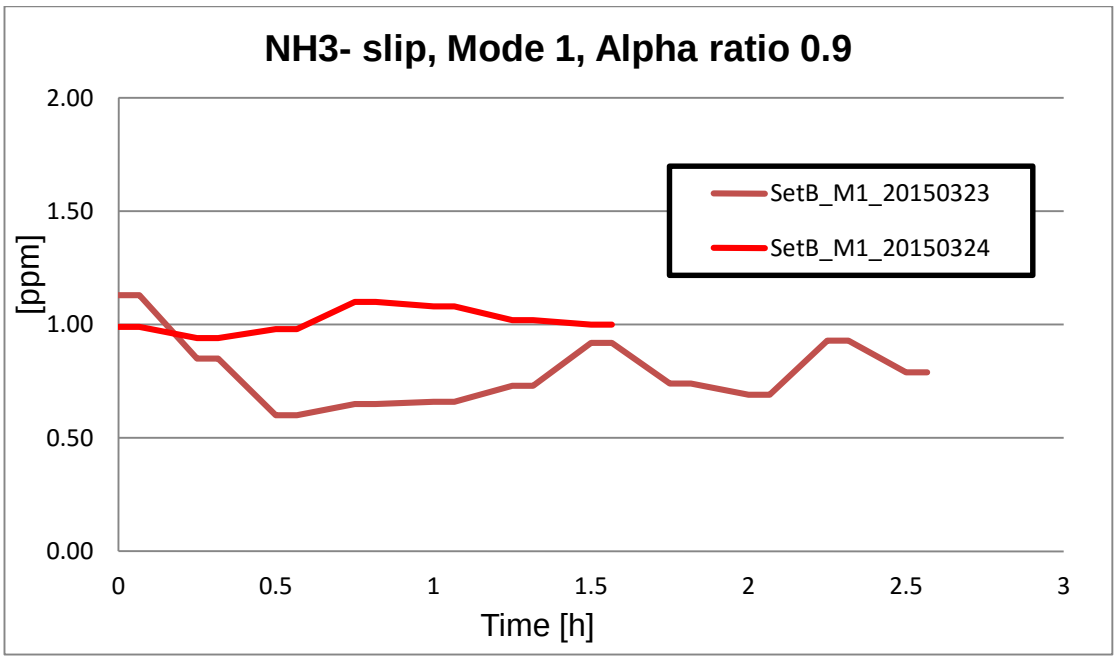


Figure 3.45. NH_3-slip for set B, Mode 1.

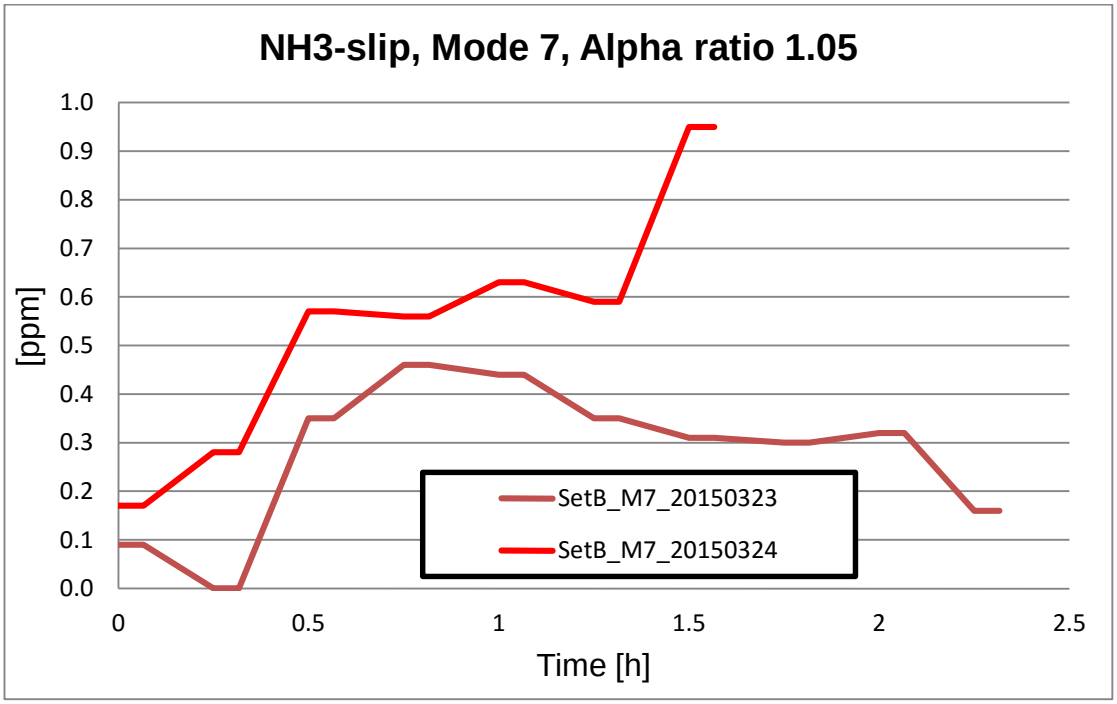


Figure 3.46. NH_3-slip for set B, Mode 7.

NO_x emissions before aftertreatment system in Mode 1 are presented in Figure 3.47. NO_x emissions in the two measurement days was between 640 ppm and 670 ppm. Figure 3.48 presents NO_x emissions for Mode 7 in the range of 660-700 ppm.

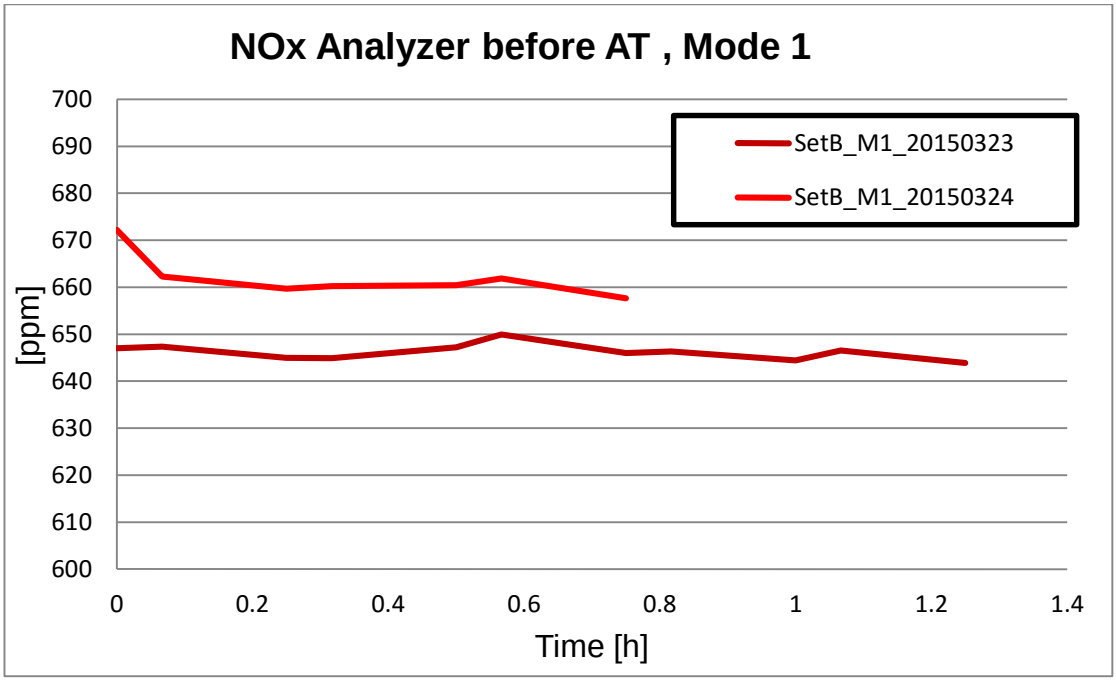


Figure 3.47. NO_x emissions before AT for set B, Mode 1.

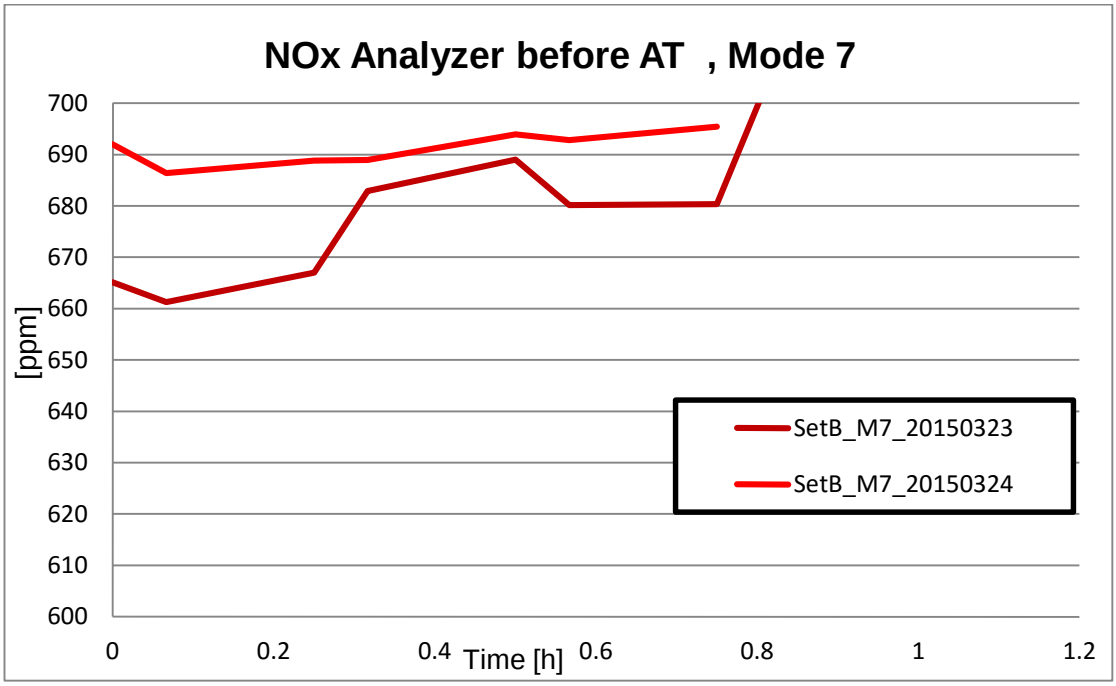


Figure 3.48. NO_x emissions before AT for set B, Mode 7.

NO_x emissions after the aftertreatment system in Mode 1 are presented in Figure 3.49. NO_x emissions in the two measurement days were between 104 ppm and 111 ppm. Figure 3.50 presents NO_x emissions for Mode 7 in the range of 30-60 ppm.

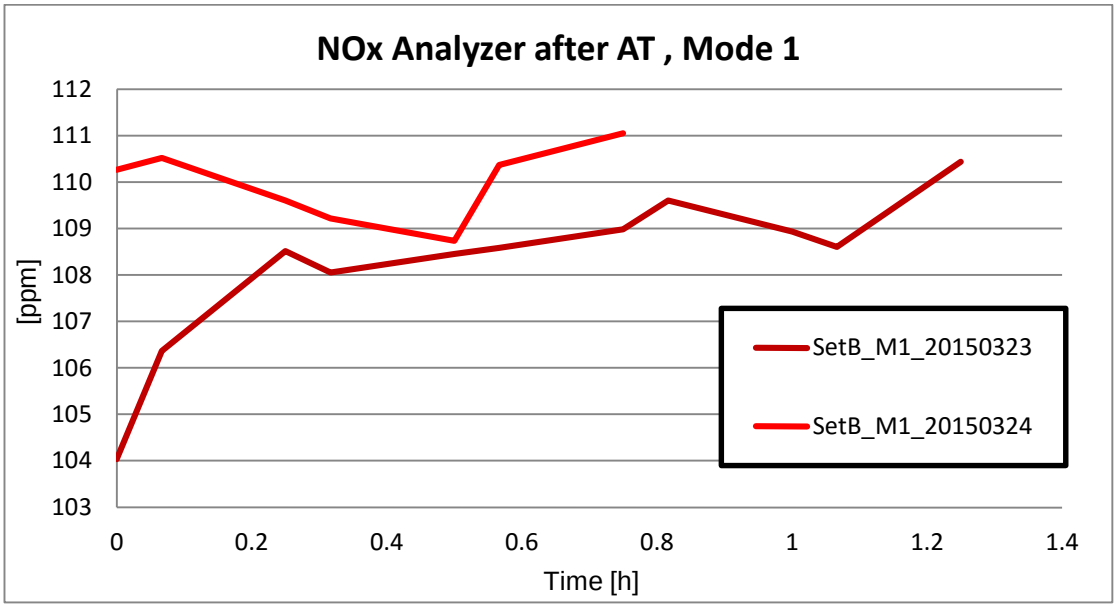


Figure 3.49. NO_x emissions after AT for set B, Mode 1.

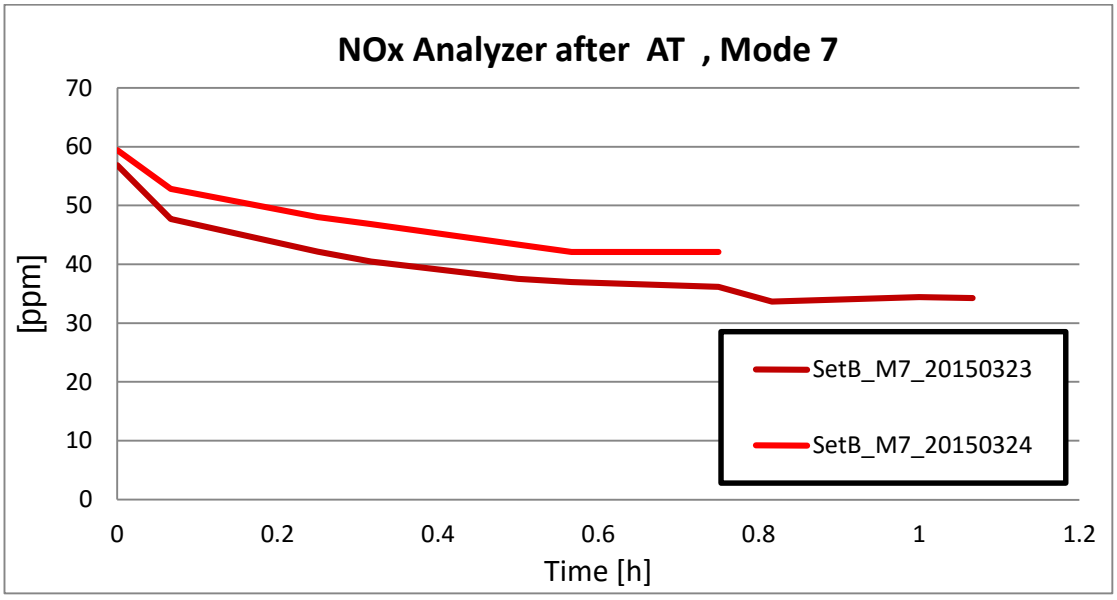


Figure 3.50. NO_x emissions after AT for set B, Mode 7.

PM emissions in Mode 1 are presented in Figure 3.51. PM emissions in the two measurement days were between 2 mg/kWh and 3 mg/kWh. Figure 3.52 presents PM emissions for Mode 7 in the range of 0.3-0.7 mg/kWh.

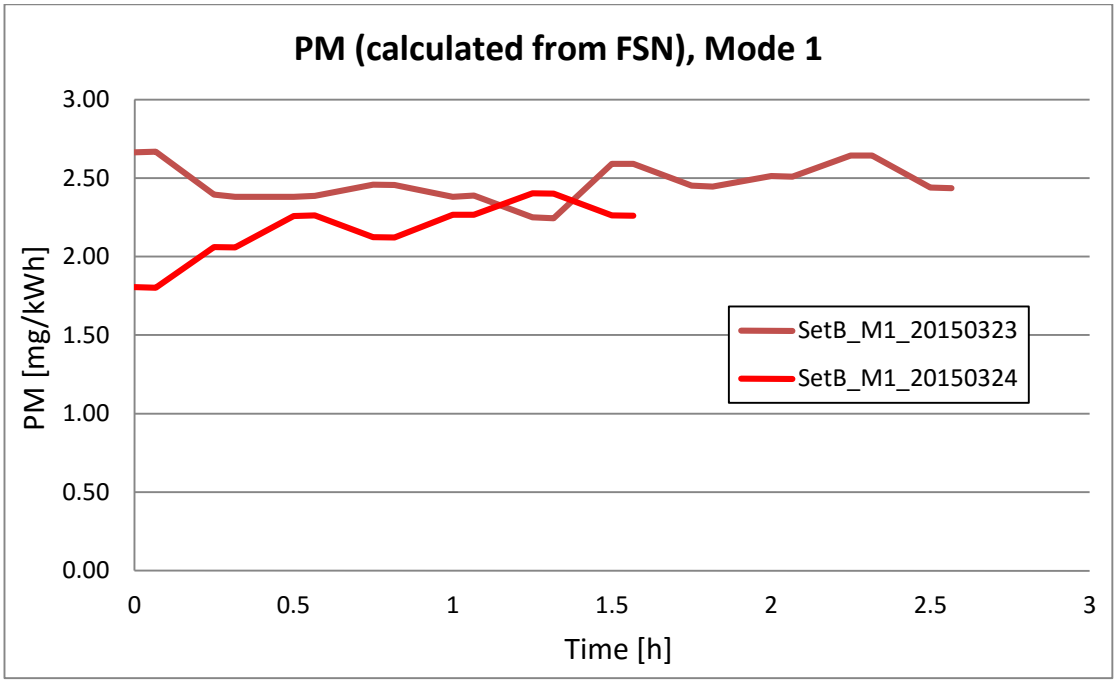


Figure 3.51. PM emissions for set B, Mode 1.

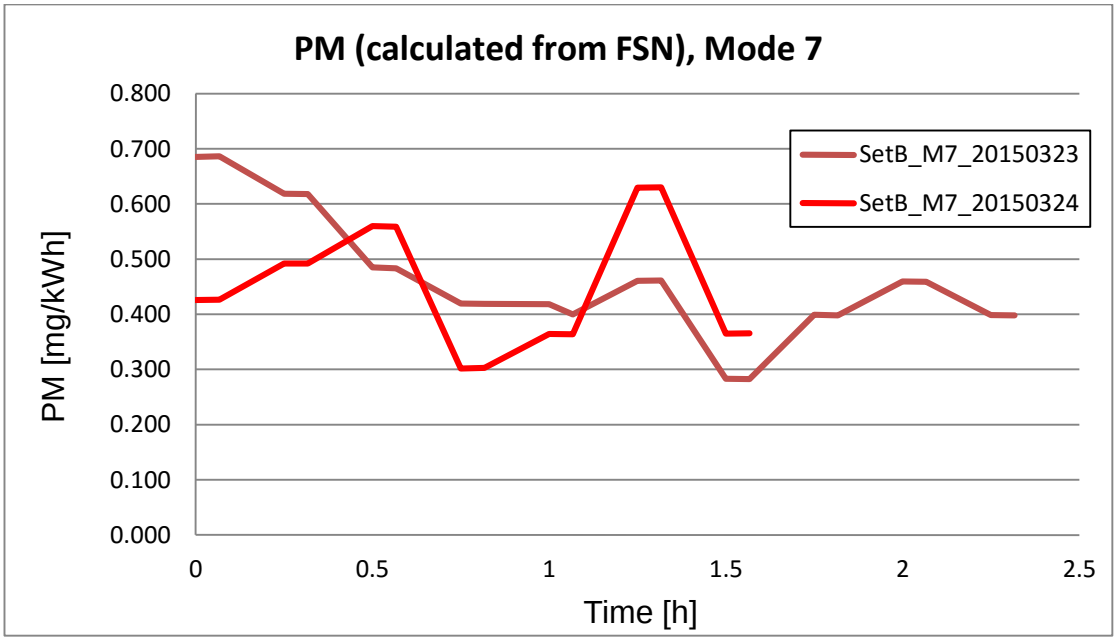


Figure 3.52. PM emissions for set B, Mode 7.

Smoke emissions in Mode 1 are presented in Figure 3.53. Smoke emissions in the two measurement days were between 0.006 FSN and 0.012 FSN. Figure 3.54 presents PM emissions for Mode 7 in the range of 0.006-0.012 FSN.

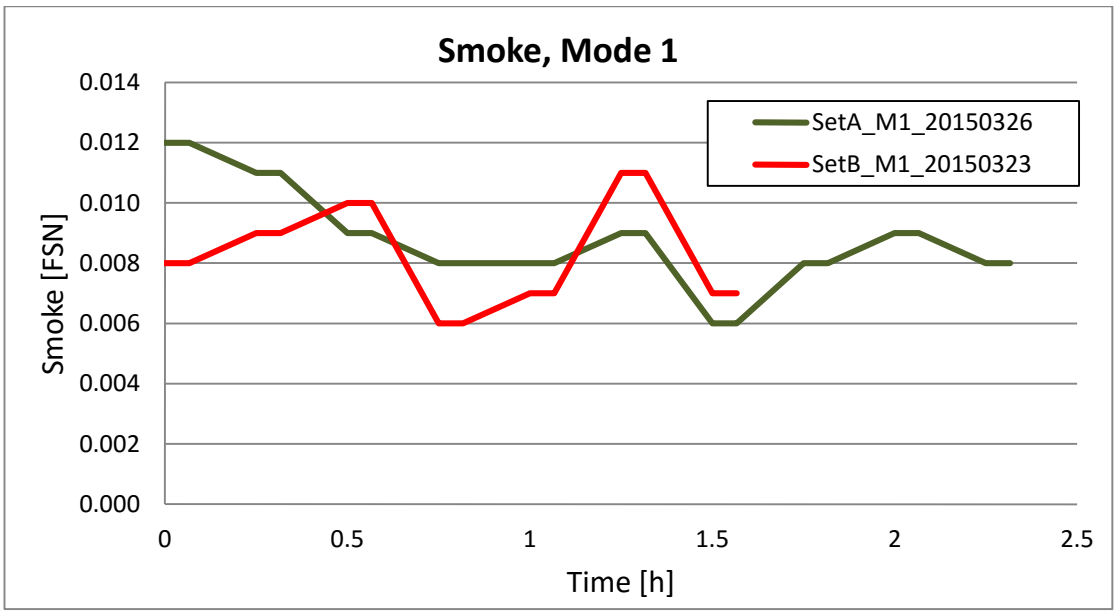


Figure 3.53. Smoke emissions for set B, Mode 1.

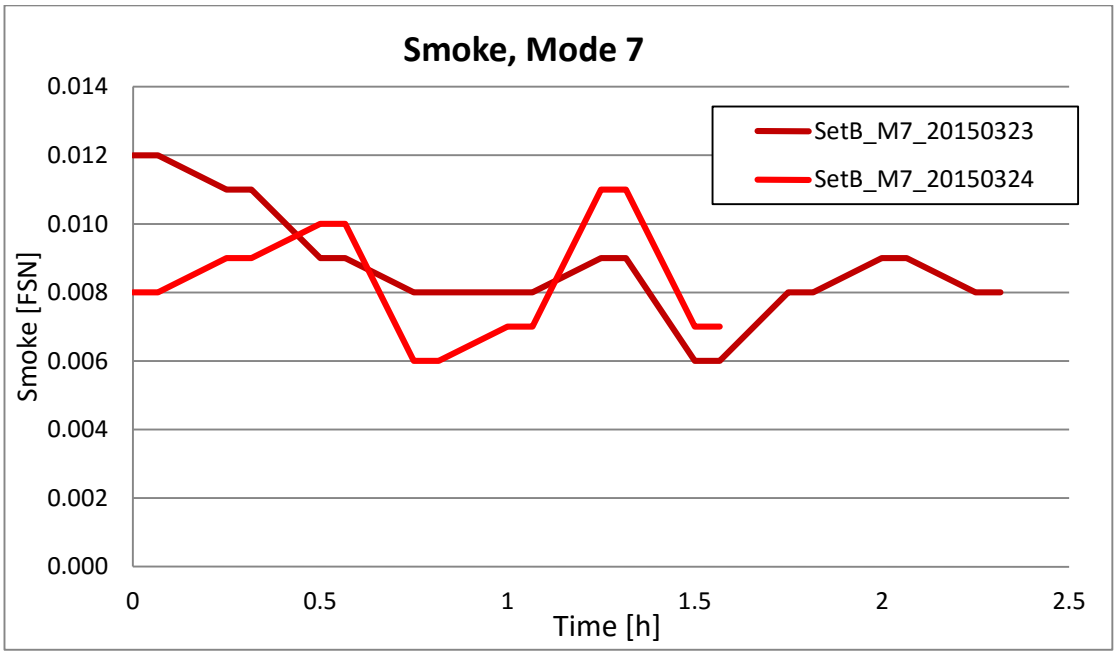


Figure 3.54. Smoke emissions for set B, Mode 7.

Fuel consumption in Mode 1 are presented in Figure 3.55. Fuel consumption in the two measurement days was between 214 g/kWh and 215 g/kWh. Figure 3.56 presents fuel consumption for Mode 7 in the range of 202-204 g/kWh.

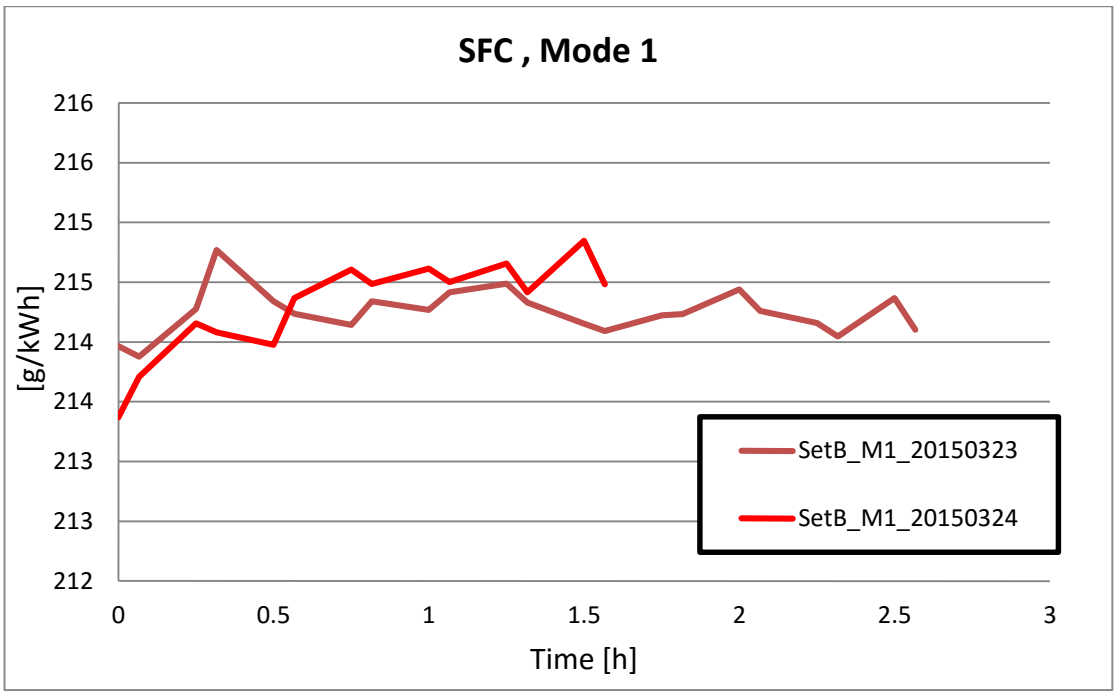


Figure 3.55. Fuel consumption for set B in Mode 1.

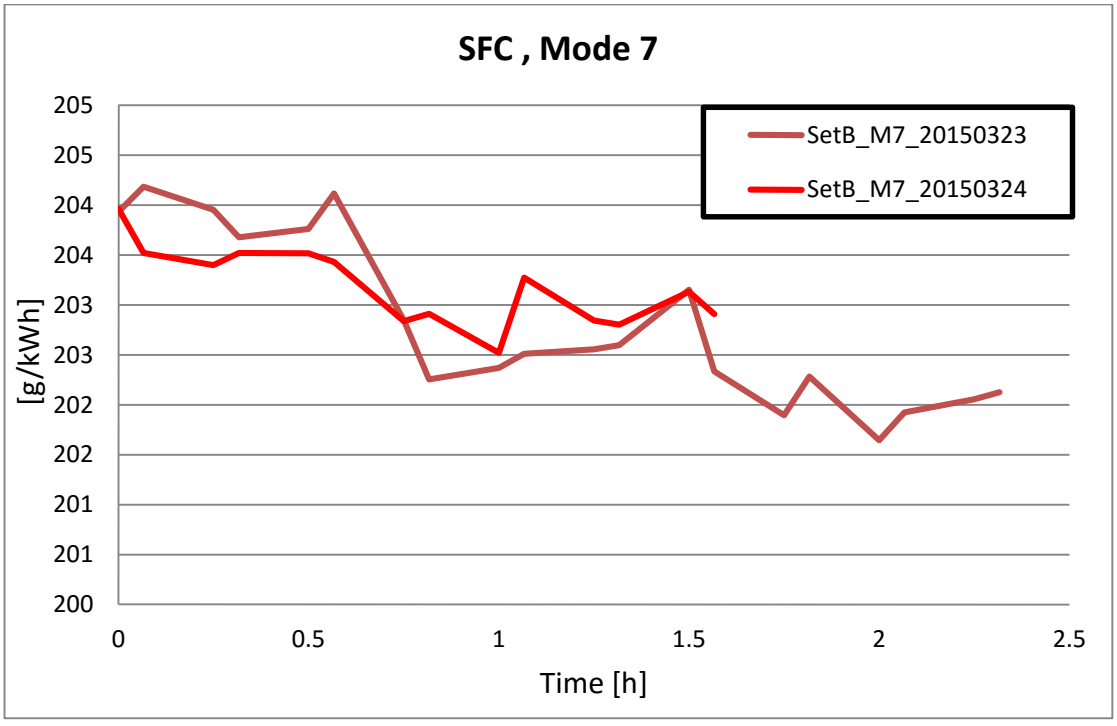


Figure 3.56. Fuel consumption for Set B in Mode 7.

Fuel flow in Mode 1 are presented in Figure 3.57. Fuel flow in the two measurement days was between 9.2 g/s and 9.3 g/s. Figure 3.58 presents fuel flow for Mode 7 in the range of 3.6-3.7 g/s.

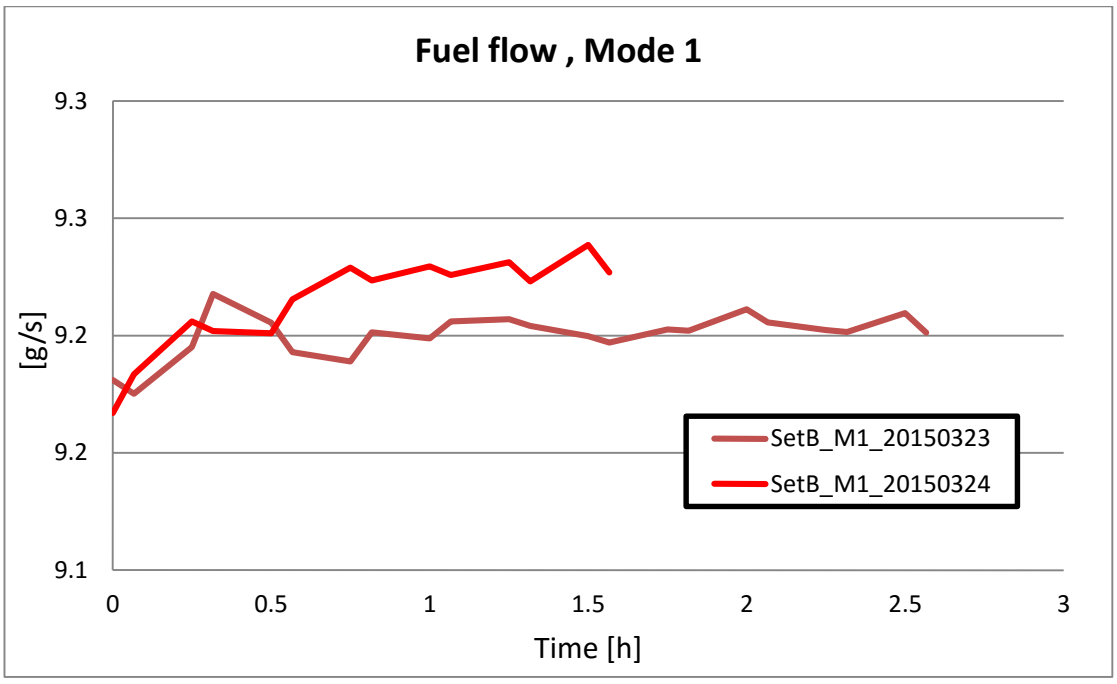


Figure 3.57. Fuel flow for set B in Mode 1.

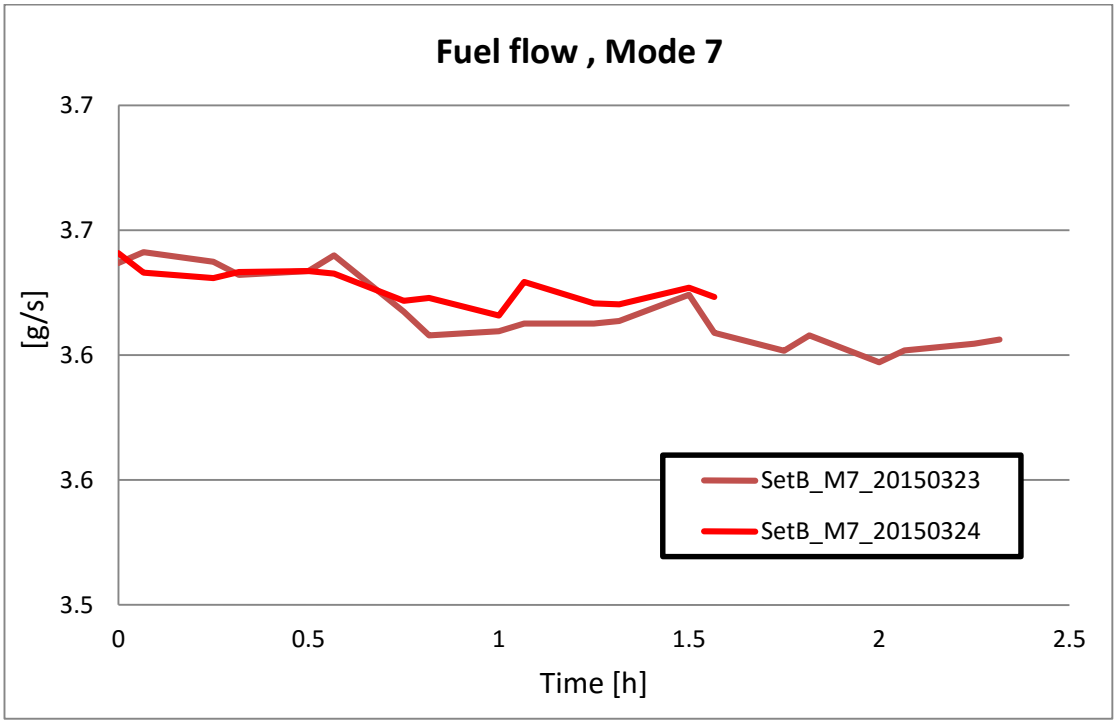


Figure 3.58. Fuel flow for set B in Mode 7.

Exhaust backpressure in Mode 1 is presented in Figure 3.59. Exhaust backpressure in the two measurement days was between 221 mbar and 228 mbar. Figure 3.60 presents fuel flow for Mode 7 in the range of 63-68 mbar.

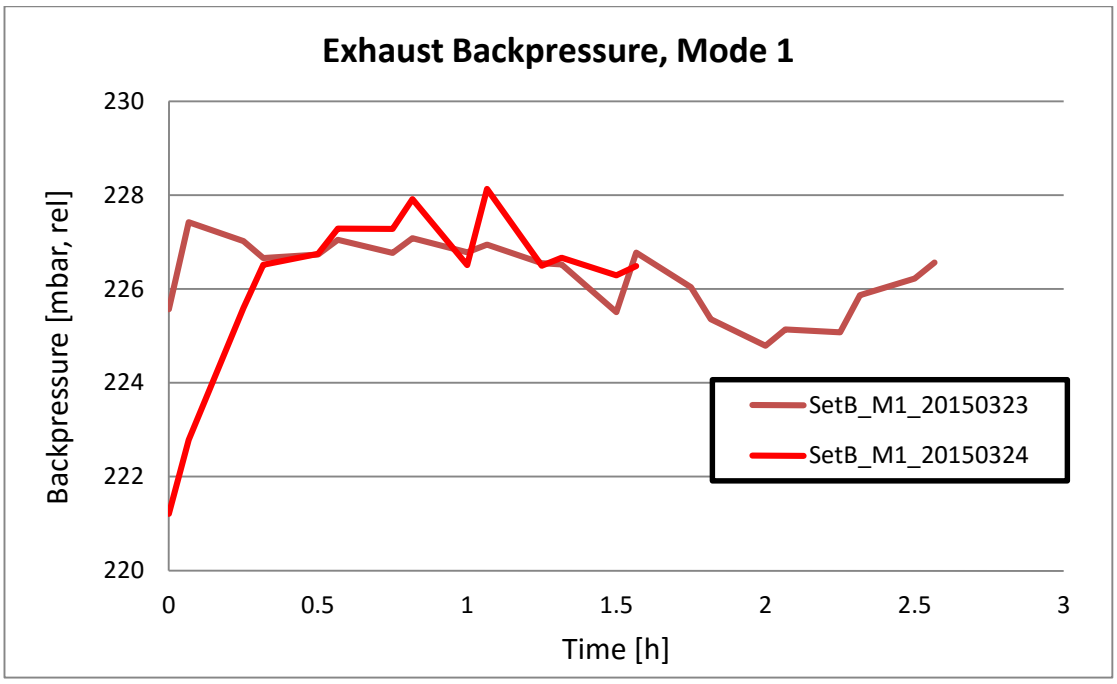


Figure 3.59. Exhaust backpressure, set B in Mode 1.

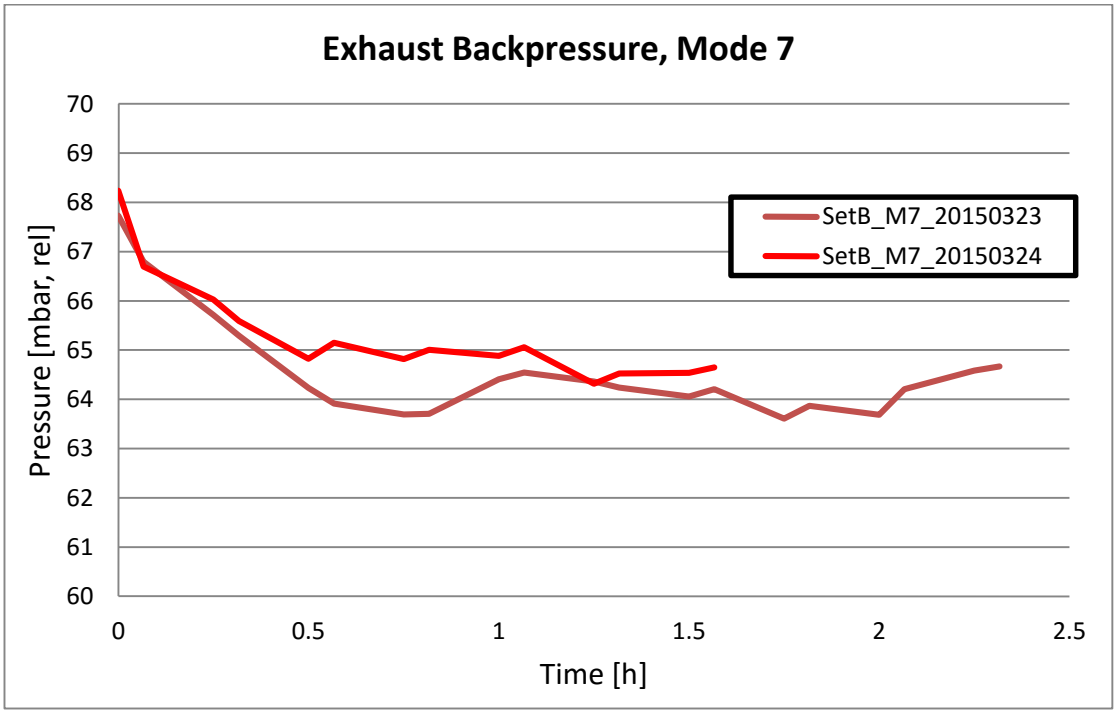


Figure 3.60. Exhaust backpressure, set B in Mode 7.

3.5 Comparison of set A and set B

In this section we will present comparative diagrams relative to the emission range measured and presented in sections 3.3 and 3.4. These results are presented for comparison in Table 3.3.

Table 3.3. Comparison of results in section 3.3-3.4.

	Set A		Set B	
	Mode 1	**Mode 7**	**Mode 1**	**Mode 7**
NOx conversion (%)	78-80	94-98	82,6-83,6	88-94
NH3-slip (ppm)	1,6-3	0-3	0,5-1,2	0-0,9
Nox before AT (ppm)	665-690	670-770	640-670	660-700
Nox after AT (ppm)	134-142	10,0-30,0	104-111	30-60
PM mg/kWh	0,05-0,4	0-0,18	2,0-3,0	0,3-0,7
Smoke (FSN)	0-0,012	0-0,04	0-0,012	0-0,012
SFC (g/kW)	213-214,5	201-204,5	214-215	202-204
Fuel flow (g/s)	9,1-9,2	3,6-3,7	9,2-9,3	3,6-3,7
Exhaust bp (mbar)	234-238	68-73	221-228	63-68

The upper values of each measured variable are plotted in order to present a clearer picture of the emissions measured in each mode of the two aftertreatment systems (Figures 3.61 and 3.62).

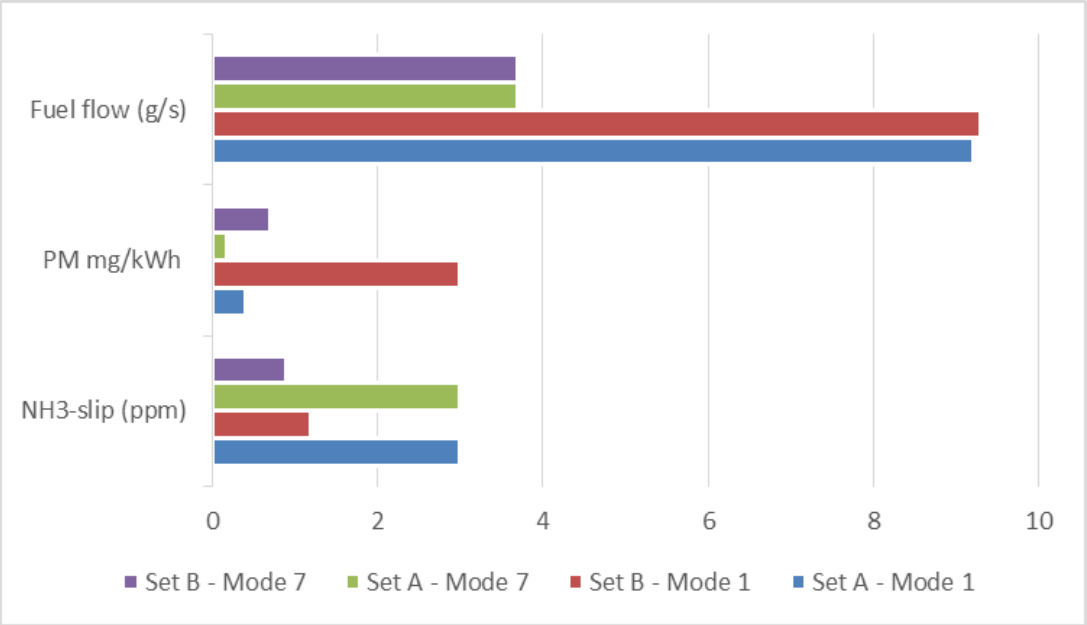


Figure 3.61. Comparison of fuel flow, PM and NH_3-slip for Mode 1 and 7 of sets A and B.

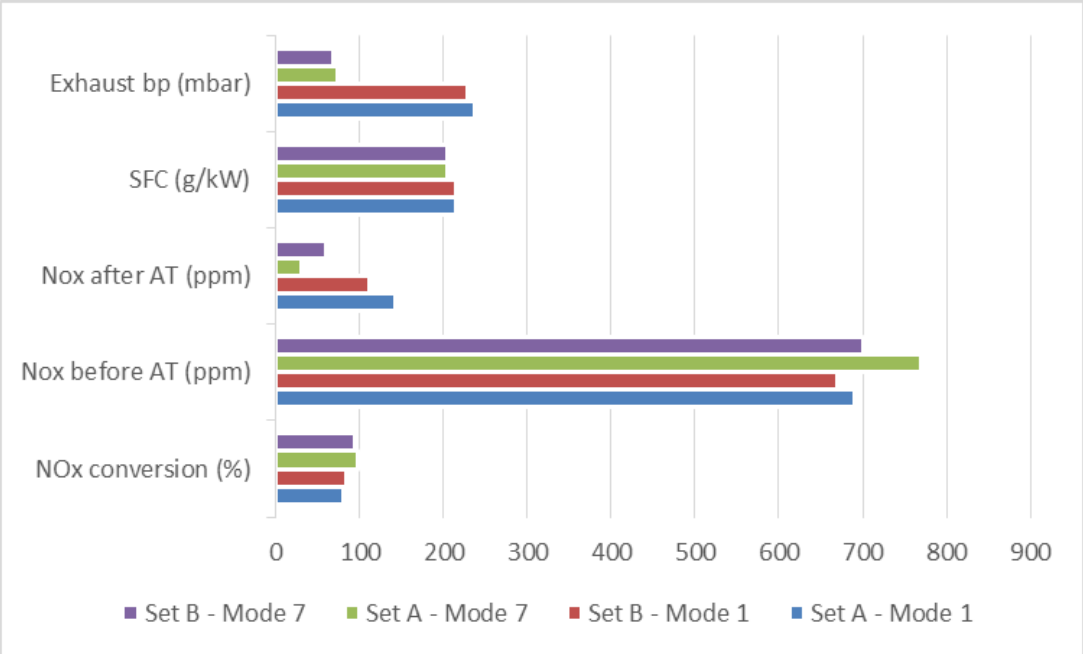


Figure 3.62. Comparison of exhaust backpressure, NO_x emissions after and before AT, SFC and NO_x conversion for mode 1 and 7 of sets A and B.

4 DISCUSSION AND CONCLUSIONS

4.1 Analysis of the Results

In Chapter 3, results are presented for the preliminary measurements and the intensive campaign results of the HERE project.

NO_x, NH_3-slip, NO_x conversion, particulate matter and smoke, fuel consumption, exhaust backpressure were measured and slip tests were conducted for the test engine with two different aftertreatment systems, Set A (DOC+fSCR+SCR88) and Set B (DOC+DPF+SCR89). Measurements are presented for Mode 1 (alpha ratio 0.9) and Mode 7 (alpha ratio 1.05) of the ISO 8178 C1-cycle.

The preliminary measurements showed that NO_x conversion efficiency of set B in soot accumulation and in regeneration was 92% for the whole measurement time. NO_x conversion efficiency of set A in soot accumulation was 94% and in regeneration 92%, but not for the whole measurement time. During the last hour of the test for set A, NO_x conversion efficiency drops at 50%. Therefore, set B presents better NO_x conversion efficiency than set A.

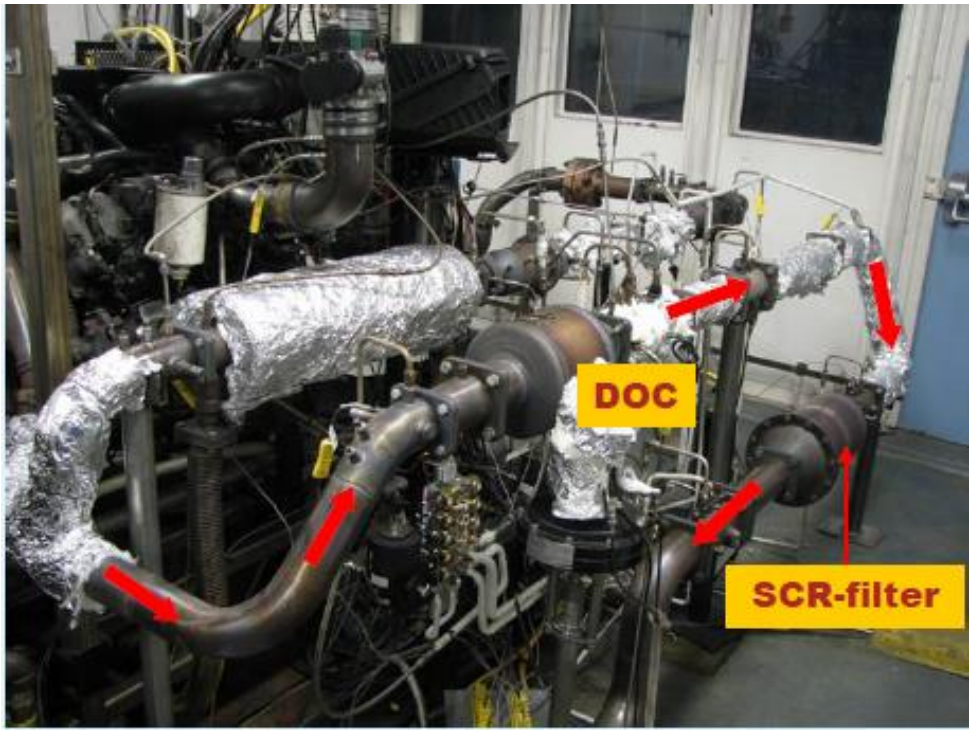
Preliminary measurements showed that NO_x emissions before AT are practically the same for both sets. After the AT, NO_x emissions for set B are reduced in a greater degree than the ones for set A. On the other hand, PM preliminary measurements showed that set A treats particulate emissions more effectively than set B. Smoke is also reduced to almost zero for set A, while for set B the measured values are low and volatile. Specific fuel consumption is almost the same in the preliminary tests for both aftertreatment sets. Fuel flow is slightly greater for set A than set B in regeneration, while in accumulation the results are practically identical. Fuel consumption differences are mainly caused in different back pressure of catalytic systems. Nitrogen monoxide emissions are slightly greater for Set A in both regeneration and soot accumulation. HC emissions after the AT systems are greater for set B in regeneration and practically the same for both sets in soot accumulation. Exhaust backpressure is greater for set A in both regeneration and soot accumulation.

After the preliminary phase, an intensive campaign followed in order to accurately measure the combined emissions for both sets A and B. NO_x emission reduction was 64% for both sets, while the NOx sensor measured 66% reduction for both sets. HC

emissions were reduced by 80% for set A and by 84% for set B. CO emissions reduction is also more effective for set B (99%) than for set A (91%). According to the combined emission results, set A presents significantly lower PM emissions than set B (PM emissions of set A are 10% of set B PM emissions). SFC is almost the same for both sets.

Next, various emission types are presented for the whole measurement time range in Mode 1 and 7 of both sets. NO_x conversion of set A is 4% lower that set B in Mode 1 and 4% higher than set B in Mode 7. In Mode 1, NOx conversion efficiency is lower than in Mode 7, for both sets. NH_3-slip of set A is greater that set B in Mode 1 and Mode 7. In Mode 1, NO_x conversion efficiency is greater than in Mode 7, for both sets. NO_x emissions of set A after the aftertreatment system are slightly greater that set B in Mode 1 and lower than set B in Mode 7. In Mode 1, NO_x emissions are greater than in Mode 7, for both sets. PM emissions for set A are significantly lower that set B in Mode 1 and slightly lower than set B Mode 7. In Mode 1, PM emissions are greater than in Mode 7 for both sets. Smoke in Mode 1 is the same for both sets but in Mode 7, set A presents greater smoke emissions. Specific fuel consumption is practically the same for both sets in both Modes while set A presents slightly lower values. In Mode 1, fuel consumption is greater than in Mode 7 for both sets. Fuel flow is practically the same for both sets in both Modes while set A presents slightly lower values. In Mode 1, fuel flow is greater than in Mode 7 for both sets. Exhaust backpressure is greater in Mode 1 than Mode 7 for both sets. Set A presents generally higher values of exhaust backpressure.

The measurement of diesel engine emission levels with ISO -8178 C1-cycle has been used by other authors (Oladipo et al., 2008, pp. 1-10). The system presented in Picture 4.1 is an engine and catalyst system. The steady state tests could be conducted by NH_3 or urea injection and the catalyst system has an SCR optimized washcoat. The aftertreatment system comprises DOC and SDPF subsystems (SCR coated on DPF system), as shown in Figure 4.1. Aging of SCR is achieved at hydrothermal procedure of 50 hours at 750 ℃ (oven-aged). The engine used in this example is a 6.6L Duramax diesel engine designed to ’04 emissions (Oladipo et al., 2008, pp. 2-3).



Picture 4.1. Engine and catalyst system.

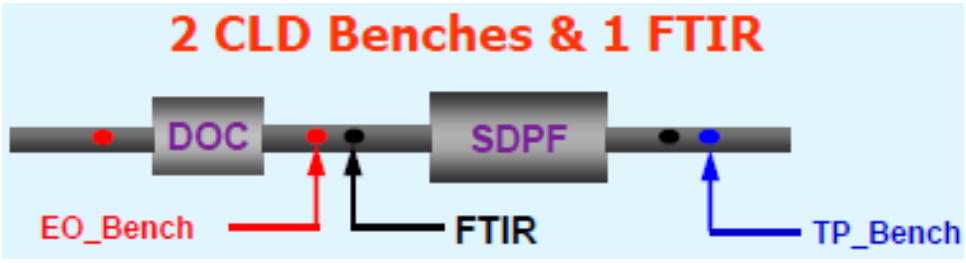


Figure 4.1. Aftertreatment system.

The SRC filter loading and coating process is optimized to minimize backpressure with cold flow tests. The setup for the DPF Soot burnout test is the following. Active regeneration follows each test and the burnout duration is approximately 20 minutes. HC dosing targeting 700 °C SDPF bed T and Exhaust Mass is 455 kg/hr while Space Velocity is 20.7 khr-1 (Oladipo et al., 2008, pp. 7-10). NH_3 vs Urea test results confirmed that urea decomposition is not a limiting factor. Back-to-back NH_3 and Urea injection minimizes

variation due to soot loading. Alpha ration is 1 for the NH_3 Injection Test. The catalyst is purged with NO_x before initiating urea to avoid impact of pre-filling with NH_3. Urea setting is adjusted to match tailpipe NO_x from NH_3 test.

With an oven-aged SCR filter NO_x conversion up to 95% is achieved. In this measurement DOC has a Pt catalyst only and the DPF is also oven-aged 48 hours at 650 ℃ with 10% pure water (Oladipo et al., 2008, pp. 10). Washcoat optimization helps minimize ΔP from SCR filter. Increase in ΔP becomes more pronounced above 1400 kg/hr of flow (Umicore, 2008). The SDPF system enhances NO_x conversion levels. Generally, the NO_x performance is argued to improve with SCR filters. Fuel flow is also reduced without an impact on NO_x conversion performance.

These results support the results of our measurements since we have shown than the fSCR filter (set A) enhances NOx conversion efficiency and improves HC and CO reduction. Fuel flow is slightly improved with the fSCR filter, but the differences with DPF are not significant. The greater effect, though, is in PM emissions that are drastically reduced in comparison to the alternate DPF filter (set B).

4.2 Conclusions of Results

Since there are no major changes and alterations observed in the results, the results can be stated to be reliable. Based on this study, aftertreatment set A seemed more promising in the reduction of emissions. Specifically, NO_x conversion is improved and CO and HC emissions are reduced. PM emissions are drastically lower due to set A (fSCR).

However, the results cannot be generalized yet since tests were implemented only for one engine (AGCO POWER 49 AWF). Nevertheless, the aftertreatment system with fSCR (DOC + fSCR + SCR 88) presented the following significant results:

- Significantly lower PM, slightly lower smoke and SFC in both studied loading points.
- Best NOx conversion in Mode 7.
- 4% lower NOx conversion than Set B in Mode 1.
- HC and CO emission level slightly better compared to Set B.
- High exhaust back pressures compared to Set B.
- Emissions are greater in Mode 1 compared to Mode 7.

5 SUMMARY

This study is a part of HERE project that aims to investigate exhaust particle emissions in order to propose aftertreatment systems that do not degrade human health and regulate energy efficiency in diesel engines. This project is funded by TEKESFiDiPro programme. Its main scope is to research particulate emissions of combustion engines and to study new methods to analyse particulate emissions. One main target is to find ways to affect emission legislation.

For this study, two aftertreatment systems were tested: one with a fSCR filter and the other with a DPF filter. DOC and SCR filters are present in both aftertreatment systems. The systems were measured in a preliminary phase which included soot accumulation and regeneration phases. Next, an intensive campaign with actual tests was implemented. In this campaign, a lot of different particulate measurement analysers are used by TUAS and other research partners. This thesis analyses and presents basic data of engine dynamometer measurements and documents how these different particulate measuring systems are used in these measurements.

This thesis consists of two parts: a theoretical review part and a part for measurement data analysis. First, in the theory part, the author reviews the diesel engine emission legislation and literature as well as particulate measurement legislation in combustion engines at the present. Pollutants and particulate emissions in diesel engines are presented in detail, PM exhaust characterization is analyzed and the technologies for emission reduction are investigated. Then, HERE project is presented in order to present the test equipment, requirements and test procedure.

The results of preliminary and intensive measurements on AGCO POWER 49 AWF diesel engine are presented and analyzed for both tested aftertreament systems (set A: DOC+fSCR+SCR88 and set B: DOC+DPF+SCR89). Results show that set A presents significantly lower PM and slightly lower HC and CO compared to set B. NO_x conversion efficiency is 4% better in Mode 7 of set A, compared to set B. Nevertheless, in Mode 1, NO_x conversion is lower by 4% compared to set B. Also, set A presents high exhaust backpressures compared to set B. In general, set A is found to be more promising in the reduction of emissions.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my supervisor, **Mika Lauren** for his patience, motivation, immense knowledge and continuous support during this research journey. His guidance and help were essential in writing this thesis.

Besides my supervisor, I take this opportunity to express gratitude to **Anniina Jaranne** in the Department of International Office, for her help and support during my last year as an exchange student in Turku.

I would also like to thank **Henna Saveljeff** for the opportunity to join her team as an intern as well as giving me the access to the laboratory and research facilities. Without her precious support, to conducting this work would not have been possible.

Finally, I would like to mention Professor **Dimitrios Prapas** for his remote yet valuable support.

6 REFERENCES

[CRES, 2015] Clean Fuels & Vehicles: Quick Guide to the "Clean" Fuels and Vehicle Technologies, Center for Renewable Energy Sources, Greece.

Abdul - Khalek, I.S., Kittelson, D.B., Graskow, B.R., Wei, Q., and Brear, F., 1998. Diesel exhaust particle Size: Measurement issues and trends, *SAE Technical Paper* No. 980525.

Dieselnet (2015) “European emission standards for cars and light vehicles”. Available online: https://www.dieselnet.com/standards/eu/ld.php

Engine Basics (2015). “Exhaust Flow and Tuning” Available online: http://www.enginebasics.com/Engine%20Basics%20Root%20Folder/Exhaust%20Flow.html

EPA, (2002). “2002 National Emissions Inventory Data & Documentation”. Available online: http://www3.epa.gov/ttnchie1/net/2002inventory.html

Hall, D., Colin D., 2003. The Effect of Sulphur-Free Diesel Fuel on the Measurement of the Number and Size Distribution of Particles Emitted from a Heavy-Duty Diesel Engine Equipped with a Catalysed Particulate Filter, *SAE Technical Paper* 2003-01-3167

Johnson, T.V., 2004. Diesel emission control technology –2003 in review, *SAE Technical Paper* No. 2004- 01-0070.

Majiewski A. (2001) “Diesel Particulate Filter”, https://www.dieselnet.com/tech/dpf.php

Majiewski A. (2005) “SCR Systems for Mobile Engines”, https://www.dieselnet.com/tech/cat_scr_mobile.php

Majiewski A. (2005) “Selective Catalytic Reduction”, https://www.dieselnet.com/tech/cat_scr.php

Ntziachristos, L, Giechaskiel, B, Pistikopoulos, P, Fysikas, E, Samaras Z., 2003. Particle emissions characteristics of different onroad vehicles. *SAE Technical Paper* No. 2003-01-1888.

Oladipo et al., (2008) Simplification of Diesel Emission Control System Packaging Using SCR Coated on DPF, 14th Diesel Engine-Efficiency and Emissions Research (DEER) Conference.

Pandazakis, A. (2014). Soot traps function measurements with simultaneous selective reduction of nitrogen oxides. Diploma thesis, NTUA Athens.

Particle Measurement Programme. Report of the GRPE Particle Measurement Programme (PMP) Government Sponsored Work Programmes July 2003. Online: http://www.unece.org/trans/doc/2002/wp29grpe/TRANSWP29-GRPE-44-inf05e.pdf.

PARTICULATES – Characterisation of Exhaust Particulates from Motor Vehicles. 5FP Project of the European Commission in the Competitive and Sustainable Growth (GROWTH) Programme, sponsored by DG TREN Contract No: 2000-RD.10429. Online: http://vergina.eng.auth.gr/mech/lat/particulates/.

Pui, D.Y.H., and Chen, D-R. (1997). Nanometer particles: A new frontier for multidisciplinary research, Journal of Aerosol Science 28, pp. 539 544.

Sakurai, H., Tobias, H.J., Park, K., Zarling, D., Docherty, K.S., Kittelson, D.B., McMurry, P.H. and Ziemann, P.J. (2003). On-line Measurements of Diesel Nanoparticle Composition and Volatility. Atmos. Environ. 37: 1199–1210

SMMT (2015) “Diesel: The facts” Available online: http://www.smmt.co.uk/industry-topics/diesel-facts/#responsiveTabs1

Thompson, N., Ntziachristos, L., Samaras, Z., Aako, P., Wass, U., Hausberger, S. and Sams, T., 2004. Overview of the European "Particulates" project on the characterization of exhaust particulate emissions from road vehicles: Results for heavy – duty engines. *SAE Technology Paper No*. 2004-01-1986.

Timothy C. Watlinga, Maya R. Ravenscrofta, Graham Avery (2011) “Development, validation and application of a model for an SCR catalyst coated diesel particulate filter”

Tobias, H.J., Beving, D.E., Ziemann, P.J., Sakurai, H., Zuk, M., McMurry, P.H., Zarling, D., Waytulonis, R. and Kittelson, D.B. (2001). Chemical Analysis of Diesel Engine Nanoparticles Using a NanoDMA/Thermal Desorption Particle Beam Mass Spectrometer. Environ. Sci. Technol. 35: 2233–2243.

Vaaraslahti, K., Virtanen, A., Ristimäki, J. and Keskinen, J. (2004). Nucleation Mode Formation in Heavy-Duty Diesel Exhaust with and without a Particulate Filter. Environ. Sci. Technol. 38: 4884-4890.

Vouitsis, E., Ntziachristos, L., and Samaras, Z. (2003). Particulate matter mass measurements for low emitting diesel powered engines: what's next? *Progress in Energy and Combustion Science* 29, 635–672.

Vouitsis, E., Ntziachristos, L., and Samaras, Z. (2005). Modelling of diesel exhaust aerosol during laboratory sampling, Atmospheric Environment.

Xatzimanolakis, (2011) Techno-economic and environmental assessment of the introduction of hybrid and diesel vehicles in the broad area of Athens, Greece. Master Thesis, NTUA.

Instrumentation (PI) diagram